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U. S. ARMY
TRANSPORTATION RESEARCH COMMAND
FORT EUSTIS, VIRGINIA

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AS AD No.

TRECOM TECHNICAL REPORT 63-44

HELICOPTER VIBRATION INDICATOR

FINAL REPORT

Task 9R38-01-017-41

October 1963

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FINAL REPORT

Task 9R38-01-017-41

TRECOM Technical Report 63-44
October 1963

HELICOPTER VIBRATION INDICATOR

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U. S. ARMY TRANSPORTATION RESEARCH COMMAND
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CONTENTS

*ILLUSTRATIONS

*Figures contained in Appendix II, contractor's final report, are not included.

TABLES*

*Tables contained in Appendix II, contractor's final report, are not included.

SUMMARY

This report covers the research and development for the design, fabrication, and evaluation testing of a helicopter vibration indication system. The project was initiated to meet a requirement for a system to detect and alert helicopter pilots to unsafe vibration levels during the operation of helicopters.

A contract was awarded to the American Research and Manufacturing Corporation to conduct the necessary research, design, and fabrication of the subject system. Upon completion, five helicopter vibration indicator (HVI) units and one vibration shake table were delivered to the United States Army Transportation Research Command (USATRECOM) for evaluation tests and comparative data analysis.

The evaluation tests were conducted by installing each HVI system in one H-21-type helicopter (in lieu of five separate H-21's) in order to obtain comparative data. The flight tests were conducted in accordance with a basic flight plan suggested by the contractor.

Evaluation test results indicated that the helicopter vibration indicators, as designed, were unsuitable for Army helicopter utilization.

CONCLUSIONS

It is concluded that:

1. The present vibration indication system, as designed, is too complex and unreliable for use on Army helicopters. For the Government to pursue any additional effort relative to improving this particular system would be economically unfeasible.

2. During the period of this contractual effort, the state of the art in electronic components has surpassed that of the present design; therefore, many of the components and circuits installed in the present units are obsolete and in some instances difficult to replace as off-the-shelf items.

3. A simpler and more reliable vibration indicator can be designed within the state of the art today.

4. Although the currently designed system did not produce consistently reliable information, much was learned regarding helicopter vibrations and the means of detecting critical vibration levels. (See especially Appendix II, contractor's report, for vibration data for various helicopter models.)

5. The results of this research program are considered to be acceptable when it is realized that the equipment is the first system ever designed which is strictly intended for helicopter installation and utilization. The effort expended under this program may be considered as a step leading toward the design and fabrication of a more reliable helicopter vibration indication system.

BACKGROUND

Vibration has been a serious problem with helicopters since the beginning of their development, and it was not until this disturbance was dampened or balanced out that helicopters could be operated successfully. Currently, helicopters which are functioning properly have relatively low levels of vibration; however, when certain components become worn, damaged, and/or out of adjustment, dangerous vibration that could destroy the aircraft can occur. At the present time, the pilot's judgement determines when vibration exceeds safe limits.

The pilot's impression of the vibration existing on military helicopters is based on subjective, qualitative information obtained through his sense of feeling, sight, and hearing. This type of information depends, to a great extent, on the pilot's physical and psychological condition and on his prior experience with the particular aircraft. A significant factor of danger is the possibility of the pilot's becoming accustomed to a dangerously high level of vibration where the change in level prior to an incipient failure is gradual.

Experience indicated the need for a helicopter vibration indication system which would augment the pilot's perception and interpretation and therefore increase flight safety substantially.

On 20 December 1956, the Transportation Corps Technical Committee approved the task for studies and investigations leading toward the design and development of a vibration indicator (see Appendix I). The indicator was to be adaptable to all Army helicopters and capable of detecting unsafe vibrational conditions and interpreting them to the pilot during flight.

In June 1957, a contract was awarded to the American Research and Manufacturing Corporation, Rockville, Maryland, to conduct the necessary research investigations for the design and fabrication of a system for determining and reporting an unsafe vibrational condition in military helicopters. The research effort under this program was accomplished in three phases:

Phase I - Determination of critical vibrations in military helicopters.

Phase II - Design and development of prototype instruments.

Phase III - Prototype construction and testing.

For a detailed record of the research effort, see Appendix II, contractor's report.

Upon completion of five helicopter vibration indicators, the units were delivered to USATRECOM, Fort Eustis, Virginia, for the purpose of conducting engineering flight tests, specific operational evaluation, calibration checkout, and comparative data analysis.

Because of the unavailability (on a priority basis) of a permanently assigned H-21 helicopter, the flight tests were conducted on an as-available basis.

Since the helicopter was detailed for special mission assignments away from Fort Eustis, Virginia, an extension of the flight test program was necessary. The flight tests were conducted during the period 14 July to 26 September 1960.

DESCRIPTION OF HELICOPTER VIBRATION INDICATOR

The helicopter vibration analyzing system consists of seven basic, functional modules, each of which may be considered as a separate unit or building block. These parts are identified as follows:

1. Reference Signal Generator
2. Oscillator Number 1
3. Oscillator Number 2
4. Vibration Pickup (Accelerometer)
5. Vibration Signal Amplifier
6. Analyzing Amplifier
7. Pilot's Display (Meter)

With the exception of items one, four, and seven, all other associated items and related components are grouped together in a single cabinet. The relative size of the entire system, which weighs 46 pounds, is depicted in Figure 1. A more detailed description regarding the system's design concept and function can be found in sections six and seven of Appendix II.

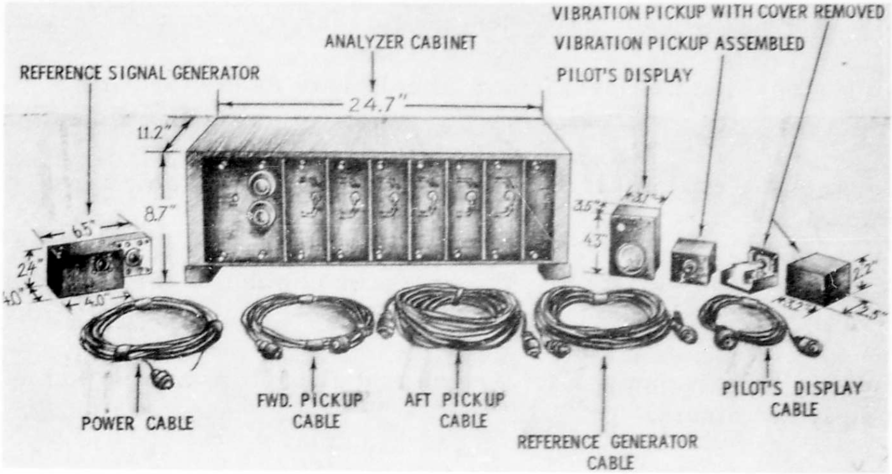

Figure 1. Helicopter Vibration Indication System.

TEST PROCEDURES AND RESULTS

DETERMINATION ONE. Calibration Procedures and Location of Problem Areas

Procedure

Upon delivery of the five helicopter vibration indication systems to Fort Eustis, calibration tests were conducted for the purposes of becoming totally familiar with the systems, of obtaining data for comparative analysis, and of establishing whether or not there were any discrepancies and/or problem areas associated with the operation of each system. It was established that the following minimum equipment is required in order to conduct the calibration tests properly:

1. Power supply of two 28-volt d.-c. sources with a 2-ampere capability. Note: One 28-volt d.-c. source must be variable.

2. One vacuum tube voltmeter (VTVM). Note: The VTVM must be capable of measuring d.-c. voltages.

3. One electronic counter, capable of measuring 300 cycles per second to 1,000 cycles per second. Note: Similar to Hewlett-Packard Model 523B.

4. One shake table (specially designed). See Appendix IV, Figure 7.

The following steps must be performed to calibrate each vibration system fully:

1. Connect the equipment as shown in the block diagram; see Figure 2 on page 9.

2. Set all switches located on the analyzer cabinet to the "calibrate" position.

3. Turn on power supply number one and allow to warm up for approximately 20 minutes.

4. Remove cover from the forward pickup and mount the unit on the shake table. See Appendix IV, Figure 7.

5. Remove the cover from the aft pickup and place the unit in an upright position on the bench. Note: This is essential in order to preclude any feedback of signals into the analyzer cabinet.

6. After warmup, set oscillators number one and number two at 2.75 volts (r.m.s.), using the VTVM to set voltage.

7. Set potentiometers number one and number two on the vibration signal amplifier at 4.00.

8. Set selector switch on the pilot's display at 1 forward channel.

9. Alternately adjust trim potentiometers on the forward pickup assembly until a minimum (null) meter reading is obtained.

10. Repeat steps 8 and 9 for aft channel.

11. Repeat step 8.

12. Set micrometer amplitude adjustment located on shake table to read 0.443 inch.

13. Shift gearing of shake table to the correct position for 1/rev. vibration signal (this position has the slowest relative speed).

14. Adjust power supply number two so that the electronic counter indicates a 10-period average reading of 354, with a tachometer reading of 105.

15. Adjust "cal. adj. " screw on the 1/rev. forward analyzer amplifier to indicate a reading of 1.0 on the pilot's display meter.

16. Shut off power supply number two.

17. Set selector on pilot's display to 2 forward channel.

18. Repeat step 12 to obtain a reading of 0.139 inch.

19. Shift gearing of shake table to the correct position for 2/rev. vibration signal (this is the center position).

20. Adjust power supply number two so that the electronic counter indicates a 10-period average reading of 181, with a tachometer reading of 210.

21. Repeat step 15 for 2/rev. forward.

22. Shut off power supply number two.

23. Set selector on pilot's display to 3 forward channel.

24. Repeat step 12 to obtain a reading of 0.174 inch.

25. Shift gearing of shake table to the correct position for 3/rev. vibration signal (this position has the fastest relative speed).

26. Adjust power supply number two so that the electronic counter indicates a 10-period average reading of 123, with a tachometer reading of 315.

27. Repeat step 15 for 3/rev. forward.

28. Shut off power supply number two.

29. Remove forward pickup from shake table and place on bench in an upright position (cables are to remain connected).

30. Mount aft pickup on shake table.

31. To begin calibration of the aft channel, repeat steps 11 through 28, substituting aft for forward.

32. Set all switches on the analyzer cabinet in the operating position.

    Note: The "cal. adj. " control must not be changed at any time after completion of the above steps.

33. Repeat step 7, setting potentiometers number one and number two at 9.50.

34. Set selector switch on pilot's display to 3 aft position.

35. Repeat steps 24, 25, and 26.

36. Adjust "opr. adj." screw on the 3/rev. aft analyzer amplifier to indicate a reading of 0.7 on the pilot's display meter.

37. Remove the thermal delay relay, mounted on the top rear of the analyzer amplifier chassis, from the 3/rev. aft channel. This is necessary in order to isolate the low-level warning circuit.

38. Adjust the "high adj." screw so that the red warning light is activated at the reading shown in step 36.

39. Replace the thermal delay relay.

40. Adjust the micrometer on the shake table to obtain a reading of 0.4 on the pilot's display meter.

41. Adjust the "low adj." screw on the 3/rev. aft channel so that the reading of 0.4 is obtained on the pilot's display meter. This warning light should become activated in approximately 5 seconds.

    Note: The time-delay period of the low alarm may be changed by means of an adjustment screw on top of the time delay relay.

42. Repeat step 24.

43. Repeat steps 37 through 39.

44. Shut off power supply number two.

45. Set selector on pilot's display to 2 aft channel.

46. Repeat steps 18 through 20.

47. Repeat steps 36 through 44 for the 2/rev. aft channel.

48. Set selector on pilot's display to 1 aft channel.

49. Repeat steps 12 through 14.

50. Repeat steps 36 through 44 for the 1/rev. aft channel.

51. Repeat steps 29 and 30 (substitute aft for forward in step 29 and forward for aft in step 30).

52. Repeat steps 34 through 50 (substitute forward for aft). Then shut off power supply number 1.

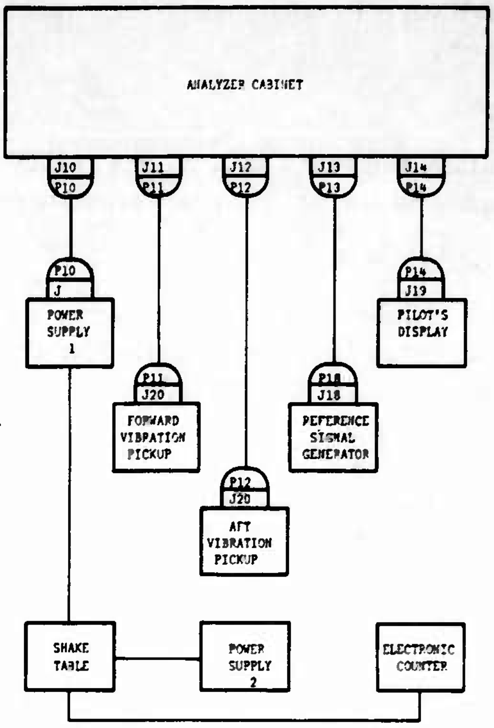

Figure 2. Block Diagram of Cable Connections for Bench Testing and Calibration of Vibration Indication System.

Results

The minimum time required to calibrate fully one complete vibration system was 1.5 hours. The maximum time required was 3 hours. Calibration tests established that after calibration related components cannot be interchanged within an individual system or with any other system without the conduction of recalibration.

Because of the variance in impedance of the electrical circuit of each channel, individual calibration curves are required for every channel of each system. See Appendix III.

Observations

During calibration of the analyzer channels, excessive meter-needle oscillations occurred in the order of 5 to 15 percent of full-scale deflection; thus difficulty in obtaining precise calibration adjustments and/or readings was encountered.

The operation of the red warning light, which indicates excessive low-level and/or high-level vibrations, was discovered to be extremely unpredictable. This was attributed to the interaction of signals between various components and the erratic operation of the thermal delay relays.

Undesirable drift in calibration was noted and observed as being a characteristic of all the vibration systems.

The individual number one and number two oscillators are not directly interchangeable with respective oscillators of the other systems. The oscillator controls in the respective oscillators must be individually matched so that the summation of the individual frequencies will produce a total frequency of 973.3 cycles per second. Any frequency other than 973.3 cycles per second causes drastic instability; therefore, it is virtually impossible to make precise calibrations. The fact that the oscillators are not directly interchangeable with each other makes this a very undesirable feature.

DETERMINATION TWO. Adequacy of Installation Procedures

Procedure

Each helicopter vibration system was installed and test flown on one H-21-type helicopter, serial number 2096, assigned to the 65th Light Helicopter Company, Fort Eustis, Virginia.

Since the helicopter was assigned on an as-available basis, the systems were installed in a temporary manner and in accordance with the installation procedures provided by the contractor. See Appendix IV; Figures 3, 4, 5, and 6 show temporary location and installation of the system.

The forward vibration pickup was mounted on the second shelf of the radio rack located on the forward left-hand side of the cabin (behind the co-pilot). The aft vibration pickup was mounted on the floor in the rear portion of the aircraft and beside the aircraft battery box.

> Note: The "cal. adj." control must not be changed at any time during the installation or operation of the system. This control is adjusted during the calibration of the system with an acceleration test table. Changes in the setting of the "cal. adj." control will necessitate recalibration of the system at a properly equipped facility.

Results

The installation procedures provided by the contractor were considered to be adequate and were easily accomplished.

The time required to accomplish the initial installation of the system was 6 man-hours.

After the initial installation, the average time required to change a complete system was 1-3/4 man-hours.

Observation

The general installation of the system is simple; consequently, no specific problems were encountered.

DETERMINATION THREE. Flight Test

Procedure

Preflight of the equipment consisted of the following steps:

1. Fifteen minutes prior to flight, equipment was turned on to permit it to warm up.

2. Oscillator voltage was checked for 2.75 volts (r.m.s.) with a vacuum tube volt meter (VTVM).

3. Selector switch on pilot's display was set to 1 forward channel.

4. Trim potentiometers on the forward pickup assembly were alternately adjusted until a minimum (null) meter reading was obtained.

5. Steps 3 and 4 were repeated for aft channel and pickup assembly.

Because the test helicopter was assigned on an as-available basis, no specific pilot was assigned to conduct the flight tests.

Each flight test was conducted in accordance with the flight test plan described in Appendix V. Six readings were recorded for each maneuver. The results are recorded in the Flight Data Comparison Charts in Appendix V.

For the purpose of readily recording the data, the pilot's display was held in the hand of the test engineer, in lieu of permanently mounting the instrument in the cockpit.

Results

The results of the flight tests are as follows:

1. Associated components such as the frequency-sensitive relays, thermo delay relays, and the output voltage of the oscillators are not operationally consistent nor reliable enough for the system to function satisfactorily. (See Appendix VI, especially pages 33, 34, and 37, where the contractor has concluded that the output charge of the oscillator is "the principal (although not the only) cause for calibration drift".)

2. After 2 hours of operation, excessive drifting of the analyzer amplifier occurred on units numbered 97V1001, 97V1002, and 97V1004.

Some amplifiers commenced to drift within 1 hour after installation in the helicopter. Thus the validity of the resultant data became questionable.

3. Under similar power settings and maneuvers, the resultant data, when compared with those of the other units, were determined not to be compatible within the agreed-upon tolerance of ± 10 percent. Furthermore, in some instances data from the same unit did not agree with its own previous data within the ± 10-percent tolerance. Differential readings as high as 114 percent were obtained, thereby indicating the unreliability of the data presented by the system. This can be readily noted in the Flight Data Comparison Charts in Appendix V.

4. Helicopter vibration units numbered 97V1003 and 97V1005 were not flight tested for the following reasons:

   a. The 3/rev. aft channel of unit number 97V1005 was totally inoperative.

   b. Calibration of unit number 97V1003 was not completed because of the lack of an appropriate power supply. The only power supply in the USATRECOM Instrument Laboratory was being utilized on another project and was not available for the time necessary to conduct the calibration.

   c. The questionable performance of the other three units and economic factors indicated no need for the testing of these units.

Observations

The total time required to preflight the equipment was 25 minutes.

Meter readings on the pilot's display were not consistent for each indication system when similar maneuvers were conducted. See results recorded in the Flight Data Comparison Charts in Appendix V.

Since no pilot was regularly assigned to conduct the flight tests, each pilot had to be briefed individually. This was considered to be detrimental to the flight test since no one pilot was thoroughly familiar with the equipment. It was observed that when a student pilot was operating the ship, the 3/rev. vibration level was much higher than that recorded when experienced pilots were flying. See Appendix VI, a report of calibration tests conducted by the contractor, which substantiates the conclusions of TRECOM engineers as to the reliability of the instrument.

APPENDIX 1

RDT & E PROJECT CARD	1. TYPE OF REPORT ☐ NEW ☒ FINAL ☐ REPLACES (No. & Date) 9R38-01-017-41, 31 Dec 59	REPORT CONTROL SYMBOL CSCRD-1(R3)
2. Task TITLE: Helicopter Vibration Indicator (U)	3. SECURITY OF Task: U	4. Task NO.: 9R38-01-017-41
	Program Element: 3753/137	6. REPORT DATE: 20 June 1961
RD Category: Aircraft and Drones	Studies and Investigations	9. CATEGORY: AR
10a. COGNIZANT AGENCY: Transportation Corps	11a. CONTRACTOR AND/OR GOVERNMENT LABORATORY	b. CONTRACT NUMBER
b. DIRECTING AGENCY: USATRECOM		
c. REQUESTING AGENCY: Transportation Corps		
12. PARTICIPATION BY OTHER MILITARY DEPTS. AND OTHER GOVT. AGENCIES: USCONARC	14. SUPPORTING PROJECTS	18. EST. COMPLETION DATES: DEV. / ENGR TEST. / USER TEST / OPERATIONAL
13. COORDINATION ACTIONS W/OTHER MILITARY DEPTS. & OTHER GOVT. AGENCIES: Canadian Army Staff	15. DATE APPROVED: 20 December 1956; 16. PRIORITY: 2; 17. BUDGET CODE: 5100	19. EST. SUPPORT LEVEL: Pr Yrs 79M; ☐ UNDER $50,000 ☐ $50,000 - $100,000 ☐ $100,000 - $250,000 ☐ $250,000 - $500,000 ☐ $500,000 - $1,000,000 ☐ OVER $1,000,000
20. No CDOG Reference	21. SPECIAL CODES	

22. REQUIREMENT AND/OR JUSTIFICATION

There is a requirement for the design and development of a vibration indicator adaptable to all Army helicopters which is capable of detecting and interpreting unsafe vibrational conditions to the pilot during flight.

23. Brief of Task and Objective:

a. Brief: Vibration has been a serious problem with helicopters since the beginning of their development, and it was not until this disturbance was dampened or balanced out that helicopters could be operated successfully. Current helicopters have relatively low levels of vibration when functioning properly; however, when certain components become worn, damaged and/or out of adjustment, dangerous vibration can occur which would destroy the aircraft. At this time, the pilot's judgment is called upon to determine when vibration exceeds safe limits. Misjudgment results in loss or damage of aircraft and personnel. The development of an instrument to detect and interpret unsafe vibrational conditions to the pilot, while in flight, is considered an excellent means of rectifying such conditions.

b. Approach: Not applicable. See Background history, par 23e.

c. Tasks: None

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TCTC ITEM 3753
MEETING 137

RDT & E PROJECT CARD CONTINUATION	REPORT DATE 20 June 1961	Task NO. 9R38-01-017-41

d. Other information: None

e. Background history and progress: This task was initiated 20 December 1956. Contract TC-430 was awarded to American Research Mfg. Co. to determine critical vibration (Phase I), design and development of prototype (Phase II), and prototype construction and testing (Phase III). Phase I was completed 19 October 1957 and Phase II was completed in July 1958. Phase III was initiated 1 September 1958 and flight testing and data reduction was completed in May 1961. Contractor's final report has been completed.

f. Future plans: None.

g. References:

(1) TCTC Item 1645, Meeting 100, held 15 December 1955, Development Project 9-39-03-001, Instrumentation Systems for Army Aircraft (U); amendment of scope approved by OCS 27 February 1956; establishing requirement for subject subtask.

(2) TCTC Item 1896, Meeting 107, held 20 December 1956, Development Project 9-89-02-000, Army Aircraft Support; revision of project approved.

(3) TCTC Item 1911, Meeting 107, held 20 December 1956, Development Subtask 128AV, Project 9-89-02-000, Helicopter Vibration Indicator; initiation approved. (Subsequently redesignated as Task 128AV).

(4) TCTC Record and Information Item 3313, Meeting 126, held 17 December 1959, Renumbering of Transportation Corps Research and Development Projects and Tasks; Changes in Titles; Redesignating Task 128AV, Project 9-89-02-000, as Task 9R38-01-017-41.

(5) Memorandum from Chief of Research and Development to Chief of Transportation, dated 4 May 1961, subject: "Review of RDT&E Program."

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APPENDIX II

HELICOPTER VIBRATION INDICATOR

Prepared by

American Research and Manufacturing Company
Rockville, Maryland

FOREWORD

This is the final report of a program for the design, development, and flight test of a helicopter vibration indication system. This program has been conducted under the sponsorship of the United States Army Transportation Research Command, Fort Eustis, Virginia, and was performed during the period July 1957 to November 1959.

CONTENTS

ILLUSTRATIONS

TABLES

1.0 INTRODUCTION

The vibration indication system will alert the pilot by means of a warning system to a dangerous condition of vibration and will, upon pilot command, supply him with quantitative information regarding the location, amplitude, and frequency of the critical vibration. With this information at his command the pilot will be better able to establish the cause of the vibration and to take necessary corrective action.

2.0 RECOMMENDATIONS

The flight tests outlined in section 8.0 were conducted during a 1-week period of intensive flight, approximately 12 to 15 hours, with the instrument installed continuously on one aircraft only. Because of the wide divergence of vibration levels to be found in each aircraft, it is recommended that additional flight tests be conducted on a broader basis, involving seven to ten aircraft at a minimum. The primary purpose of this test program would be to establish statistically the vibration limits to be applied to the H-21 helicopter. It is suggested that the flight plan outlined in the appendix be employed during the program.

It is further recommended that the fore-mentioned test program be conducted at one station only. The purpose of this recommendation is to facilitate calibration checks on the vibration shake table (see ArmCorp Report TR-97-004).

It is recommended that one instrument be subjected to temperature and environmental tests. These tests should be conducted concurrently with the flight test program.

Pending the results of the suggested test program, it is recommended that the vibration pickups be located in the following positions: (a) forward pickup, immediately below the forward drive shaft just aft of the forward transmission; (b) aft pickup, in the central transmission compartment on the cargo deck.

It is recommended that the vibration acceleration limits specified in Table 6 be considered for "provisional" status as alarm level adjustments on the instrument. It is further recommended that these limits be reviewed and revised, if required, at the conclusion of the recommended flight test programs.

In view of the extensive interest expressed by Army maintenance personnel, it is recommended that serious consideration be given to the several alternate applications outlined in section 7.0.

3.0 DISCUSSION OF HELICOPTER VIBRATIONS

Vibrations are induced by the helicopter; their primary sources are the periodic aerodynamic forces of the rotors and periodic forces of the engine. These forces are transmitted to the fuselage and structure through the rotor hubs and controls and through the engine mounts and drive shaft.

The amplitude at which the structure will vibrate depends on the relationship between the inertial and dampening characteristics of the structure and on the magnitude, direction, and frequency of the driving force. This motion of the structure is complex and is known to be detrimental to the safety of the helicopter through (a) structural failure by fatigue and (b) physical and psychological discomfort and fatigue of the pilot.

The main rotor is the principal source of vibration; the tail rotor, second; the engine, third. The vibratory forces of the engine are better understood, and the techniques for reducing, isolating, or completely eliminating the vibration are widely employed. The vibrations attributed to the main rotor and tail rotor are not as well understood.

The forces acting on the main rotor are repeated periodically for each revolution. Thus the frequency of vibration of the blades is equal to whole digit multiples of the rotor angular velocity. Ideally, the forces acting on each blade are identical, and the net force transmitted to the rotor hubs and controls is the algebraic sum of the forces acting on each blade. According to the best available understanding of the rotors, only forces at frequencies equal to whole digit multiples of the number of blades times the rotor angular velocity would be transmitted to the structure. In actual practice, however, a predominant 1/rev. vibration can exist because of the misalignment of one blade; other "odd" frequencies have been noted on particular helicopters. A detailed explanation of the significance and meaning of these "odd" frequency vibrations is not available; however, they have been attributed to misalignment, imbalance, and limitations in fabrication and assembly techniques.

Vibration data for various model helicopters are presented in section 9.0 of this report. These data show that the magnitude of the forces transmitted to the fuselage varies with forward speed, gross weight, distribution of cargo, and numerous other factors. The forces and the resulting vibrations differ considerably in helicopters of the same model according to the adjustment of the blades and various components and to minor differences in fabrication and assembly.

The effect of the vibration on the fuselage structure, transmission, and other components can be critical, particularly when a resonant condition exists (when the natural frequency of the structural component is close to or coincides with one of the frequencies of the driving force). A condition of resonance and also any self-excited vibration should be corrected by redesign.

A normal or acceptable level of vibration at each of the several frequencies is characteristic of each ship. The normal level is a function of speed, power setting, weight, and several other factors. In a sense, a normal or acceptable band may be prescribed for each ship. In addition, a normal level may be exceeded for short durations of time during maneuvering and acceleration and under rough-air conditions. Finally, an upper safe limit to the level of vibration may be prescribed for each ship.

A criterion for safety based on the normal or acceptable amplitude of vibration may therefore be established. This criterion may be stated as follows: a change in amplitude at any of the several main rotor or tail rotor frequencies reflects a change in the driving force or a change in the structure of the rotors or in their attachment to the fuselage. A change in the driving force is considered unsafe if the reason for the change is not known. A change in structure is always considered unsafe.

4.0 THE PILOT IN RELATION TO THE VIBRATION

The following discussion of helicopter vibration is related to the pilot; however, within its own limits the discussion is also applicable to passenger and crew members. The extent to which the vibration is considered critical will, or course, be different in each case.

The pilot's impression of the vibration is based on subjective, qualitative information obtained through his sense of feeling, sight, and hearing. During flight he becomes attuned or accustomed to a given level of vibration and its several changes with speed, power setting, etc. When the relationship changes in a manner that he cannot understand or is unaccustomed to, he senses a danger. However, since the type of information that he has at the present time can be misleading, a pilot cannot be expected to distinguish the frequency of a vibration unless it be a very predominate 1/rev. Also, it is possible for him to become accustomed to a dangerously high level of vibration if the change is gradual.

The complex process of analysis that the pilot presently employs in evaluating the vibration involves (a) perception, (b) interpretation, (c) decision, and (d) reaction. When one considers the number of other constant demands on the pilot's attention, it is not altogether surprising that errors are often attributed even to experienced pilots. Failure to perceive and misinterpretation are the principal sources of error. The helicopter vibration indication system has been designed to augment the pilot's perception and interpretation and will substantially increase flight safety.

5.0 DESIGN CONCEPT, FLIGHT INSTRUMENT

The vibration analyzing system consists of seven basic, functional items, each of which may be considered as a separate unit or building block. The block diagram in Figure 1 depicts a vibration analyzing system for analyzing a vibration signal at one frequency and for one particular location. Depending on the number of frequencies and locations of interest

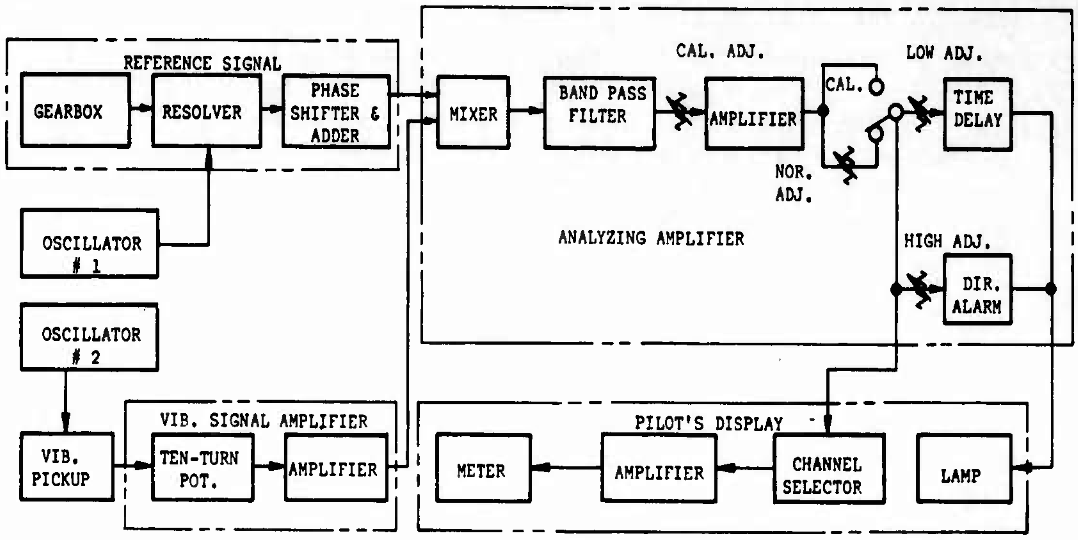

Figure 1. Vibration Analyzing System

in a particular ship, additional identical units may be added to complete a system. The vibration pickup noted in Figure 1 is a Schaevitz model VG-10 accelerometer. This unit is essentially a spring-mounted, dampened, linear variable differential transformer (LVDT) with a natural frequency of 65 cycles per second and a maximum output voltage of 1.0 volt. The amplitude of the signal from the accelerometer is directly proportional to acceleration for frequencies up to approximately 40 cycles per second. The accelerometer is powered by carrier oscillator number two at a frequency of 660.7 cycles per second. The carrier signal is modulated by the motion of the LVDT. The output signal is carrier-suppressed and contains both side bands.

The vibration signal amplifier consists of a 10-turn, 1,000-division potentiometer and an amplifier. The carrier signal output of the accelerometer, modulated by the complex vibration signal, is fed through the potentiometer to the amplifier. The potentiometer is used in order to permit the system to have the required sensitivity to low vibration levels without being overdriven at high vibration levels. The potentiometer may be adjusted to cover any 10:1 range between .01 to 10g. The amplifier is a conventional two-stage transistor amplifier.

The reference signal channel consists of an Eclipse-Pioneer resolver model AY-543-5, a gearbox, and a phase shifter and adder. The gearbox is mechanically driven by the helicopter's engine transmission or some portion of the rotor system and in turn drives the resolver at the desired rotational frequency (1M, 3M, 1T, etc.).* The resolver is powered by carrier oscillator number one at a frequency of 312.6 cycles per second. The carrier is modulated by the referenced rotational frequency. The phase shifter and adder eliminates the carrier and one side band.

The two signals from the reference signal channel and from the vibration signal channel are fed to the mixer of the analyzing and alarm channel. The modulated signal from the vibration channel with the upper side band combines with the modulated signal from the reference channel with a lower side band to give an output frequency equal to the sum of the two carrier signals when the two side bands are exactly equal. The band-pass filter passes only a signal equal to the sum of the two carrier signals, 973.3 cycles per second. The output signal will be 973.3 cycles per second only when the vibration frequency is equal to the reference frequency. The amplitude of this 973.3 cycles per second signal is proportional to the component of acceleration at the reference frequency.

The calibration—adjustment control permits the input to the amplifier to be adjusted so that the actual acceleration level may be read on the meter. The calibration—operation switch on the output of the amplifier must be in the calibration position to obtain this reading.

When the switch is in the operation position, the normal-level adjustment permits the meter reading to be set at a percentage of a particular vibration level. In this manner the output to the meter from the several analyzing and alarm channels may be adjusted to give the same meter readings at one air speed, rotor speed, and gross weight. Thus, the meter readings at each of the several frequencies of interest will fall in a band on the meter that for purposes of the pilot's interpretation may be considered to be "safe".

The output from the calibration—operation switch is fed to two frequency-sensitive, resonant-reed relays. These reeds are frequency-sensitive to 973.3 cycles per second and insure that only a signal at this frequency will close the relays of the alarm system. Two separate circuits are employed: the first, the low-amplitude alarm circuit, consists of a frequency-sensitive relay, an alarm relay, and a time-delay relay; the second, the high-amplitude alarm circuit, consists of a frequency-sensitive relay and an alarm relay.

When the vibration reaches a level which would be dangerous if sustained, the time-delay relay closes after a preset length of time, and a red lamp is lighted in the pilot's display. If the vibration reaches a "never

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* M - main rotor, T - tail rotor.

exceed" level, the high-amplitude circuit relay operates, and the red lamp is lighted immediately.

The pilot's display consists of a channel selector switch, an amplifier, a meter, and a red lamp. When either of the two levels has been exceeded, the lamp is energized through the alarm circuits. The channel selector is manually operated by the pilot, and the signal from the analyzing circuit is amplified and transmitted to the meter.

6.0 ALTERNATE SYSTEM APPLICATIONS

The system's concept and several of the principal circuits developed under this contract could be successfully employed in the design of an instrument for maintenance use and for establishing acceleration limits during acceptance tests. Two basic forms of this instrument will be discussed briefly: the first may be designated as a fixed-frequency system and the second as a frequency-spectrum system. Two approaches to the problem of designing a frequency-spectrum system are outlined.

Figure 2 represents the block diagram of the fixed-frequency instrument. As might be suspected, this system retains many of the existing flight instrument circuits. A frequency selector and location selector have

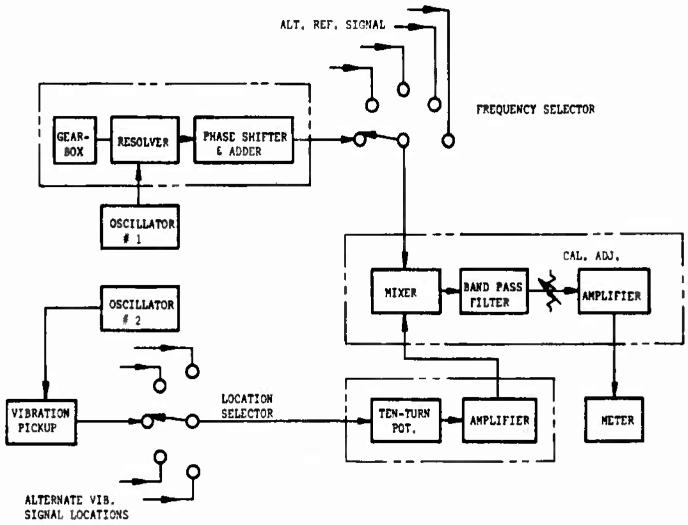

Figure 2. Fixed-Frequency System

been added and the alarm circuits and lamp removed. The amplification stage previously located in the pilot's display has been moved back and included in the analyzing amplifier. The particular advantage of this system lies in the fact that it employs basic circuits presently developed. It is, as a matter of fact, a simplification of the flight instrument.

As in the case of the flight instrument, the resolvers are gear-driven from the transmission, and the reference signal is applied to the analyzer through a selector switch. The vibration signal from one of several pickup locations is amplified and fed to the analyzer. The analyzer output signal, which is proportional to the acceleration, may be observed on the meter. Each of the several pickup locations for the several selected frequencies of interest may be manually recorded.

Figure 3 represents the block diagram of a frequency-spectrum system, which is similar to the preceding system. In place of a transmission-driven

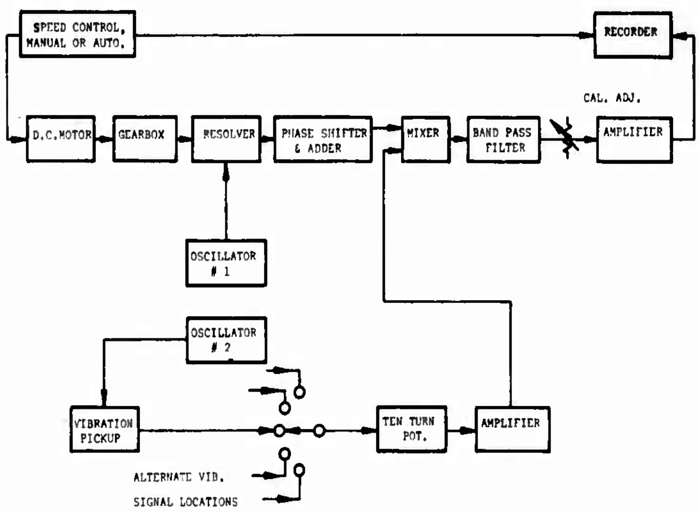

Figure 3. Frequency-Spectrum System

resolver at selected frequencies, there is a d.-c. motor driving the resolver. The frequency of the motor is automatically controlled at a constant acceleration so as to cover the frequency spectrum of interest. The same signal that controls the d.-c. motor also controls the drive of the chart recorder, which records the output of the analyzer. The recorder would be the paper-chart type with the drive motor synchronized with the rate of frequency change from the analyzer.

In this manner, the frequency-acceleration spectrum at each of the selected vibration pickup locations may be recorded as a plot of frequency versus amplitude.

The helicopter vibration indication system designed and built by this company as a synchronized frequency analyzer is adaptable for use as a spectrum analyzer. The method requiring a minimum of modification substitutes a variable-speed motor drive for the reference generators which normally are driven by the rotor-tachometer drive on the helicopter. The frequency of interest is selected by manually changing the speed of the drive motor. This system is shown in Figure 3. The output to the analyzer channel is a single-side-band, carrier-suppressed signal whose frequency is equal to the reference carrier frequency minus the reference frequency determined by the speed of the drive motor.

This method of obtaining the reference signal is necessary in the synchronized frequency analyzer where the drive from the rotor insures that the vibration frequency being measured is the same as the rotor frequency. However, in the spectrum analyzer the only important consideration is that the frequency of the signal fed to the analyzer channel be equal to the reference carrier frequency minus the frequency of the vibration signal to be measured. Therefore, in the spectrum analyzer the components shown in Figure 4 may be replaced with a variable-frequency oscillator having the proper frequency range. The control dial of the oscillator is calibrated in terms of the vibration frequency being measured. A block diagram of the spectrum analyzer is shown in Figure 5.

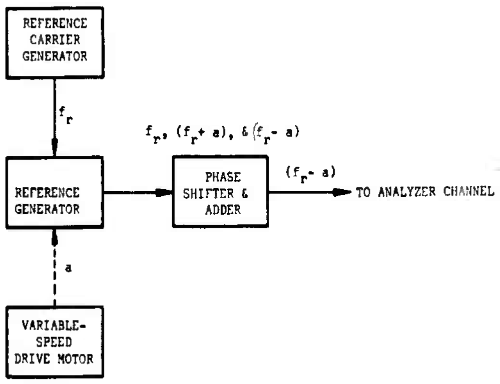

Figure 4. Manually Controlled Spectrum Analyzer

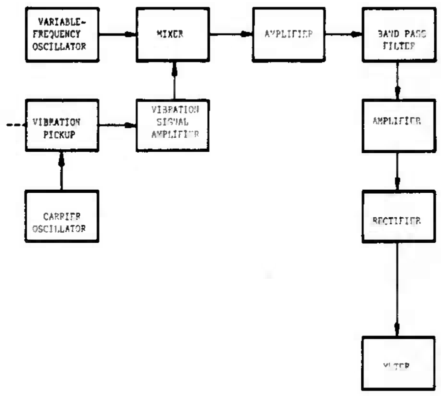

Figure 5. Spectrum Analyzer

This type of spectrum analyzer readily lends itself to use as an automatic fourier servo analyzer for determining the frequency versus amplitude components of any complex vibration waveform within the range of the instrument. In this application, the output of the analyzer is fed to the galvanometer pen of a chart recorder. The chart drive of the recorder is coupled to the variable-frequency oscillator in such a manner that the rate of frequency change of the oscillator corresponds to the rate of movement of the recorder chart. In use, the analyzer scans the frequency spectrum, and the recorder pen traces a continuous plot showing the vibration amplitude at each frequency throughout the spectrum.

7.0 PACKAGING, VOLUME, AND WEIGHT

The helicopter vibration indication system has been designed for installation in several military helicopters. Because of the variation in vibration characteristics of each of the several helicopters, it was decided to employ a module concept of design. The unique requirements of each helicopter could best be satisfied by assembling the modules in various packages. Table 1 defines the frequencies at which a critical vibration could exist for each of the several military helicopters considered in this design.

TABLE 1
CRITICAL VIBRATION FREQUENCIES

Manufacturer	Model	Monitored Frequencies
Sikorsky	H-19	1M, 3M, 1T
	H-34	1M, 4M, 1T
	H-37	1M, 5M, 1T
Vertol	H-25	1F, 3F, 1A, 3A
	H-21	1F, 2F*, 3F, 1A, 2A*, 3A
Bell	H-13	1M, 2M, 4M, 1T
	XH-40	1M, 2M, 4M, 1T

M - main rotor
T - tail rotor
F - forward rotor
A - aft rotor

The numeral preceding the letter designation defines the fundamental and harmonics to be monitored.

*In general, only the harmonics which are whole-digit multiples of the number of blades contribute to over-all vibration of the helicopter; however, in the instance of the H-21 helicopter, the preponderance of existing vibration data indicates that an important contribution of the complex vibration is at twice the main rotor speed.

In the interest of greater ease of maintenance, flexibility of design, and improved logistics for the several military helicopters under consideration, a module-type construction has been employed in the design of the helicopter vibration analyzing system. The elements of the design selected as basic modules are as follows:

Analyzing and Alarm Channel - Consists of one mixer, one band-pass filter (973.3 cycles per second), one calibration-adjustment potentiometer, one amplifier, one normal-adjustment potentiometer, one calibration-operation switch, one low-amplitude alarm circuit, and one high-amplitude alarm circuit.

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	H-21	1F, 2F*, 3F, 1A, 2A*, 3A
Bell	H-13	1M, 2M, 4M, 1T
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Vibration Signal Amplifier - Consists of two range switches and two amplifiers.

Carrier Oscillator Number One (312.6 cycles per second) - Consists exclusively of the oscillator.

Carrier Oscillator Number Two (660.7 cycles per second) - Consists exclusively of the oscillator.

Vibration Signal Channel - Consists exclusively of one LVDT.

Pilot's Display - Consists of one channel selector, one amplifier, and one lamp.

A system for any of the several military helicopters considered in this design study may be built from the six basic modules. Modules one through four are grouped together and mounted in a single chassis. Module five is located in the vicinity of the main and tail rotor, and module six is located in the pilot's cabin.

The number of modules required for a complete helicopter vibration system and the size of chassis will depend on the particular requirements for each helicopter. Table 2 defines the number of modules and the volume of the chassis required for each particular ship presently under consideration. Module five, the vibration signal channel, has a total volume for two channels of 40 cubic inches. Module six, the pilot's display, has a volume of approximately 50 cubic inches.

TABLE 2
NUMBER OF CHASSIS MODULES AND TOTAL VOLUME

Manufacturer	Model	Modules 1	2	3	4	5	6	Total Volume (cu. in.)
Sikorsky	H-19	3	1	1	1	2	1	1750
	H-34	3	1	1	1	2	1	1750
	H-37	3	1	1	1	2	1	1750
Vertol	H-25	4	1	1	1	2	1	1950
	H-21	6	1	1	1	2	1	2400
Bell	H-13	4	1	1	1	2	1	1950
	XH-40	4	1	1	1	2	1	1950

The final item of packaging to be considered is the reference signal channel. Because the gearbox requirements for each helicopter will vary with the location and mounting point of the mechanical drive, the possibility of designing a single module suitable for all helicopters is precluded. A design study for the H-21 helicopter has been conducted, and it is deemed advisable to locate the reference signal channel at the central transmission on the tachometer generator pad. An adapter has been incorporated in the gearbox so that the tachometer generator may be mounted on the transmission and continuous operation of the tachometer generator maintained.

The weight of the unit as installed in the helicopter is given in Table 3. These weights are estimated on the basis of the actual weight of the prototype unit as installed in the H-21 helicopter.

TABLE 3
WEIGHT OF INSTALLED UNITS

Manufacturer	Model	Estimated Weight (lb.)
Sikorsky	H-19	34.5
	H-34	34.5
	H-37	34.5
Vertol	H-25	38.8
	H-21	46.1*
Bell	H-13	38.8
	XH-40	38.8

* Actual Weight

The estimated cost of components for the helicopter vibration analyzing system (as installed in the H-21 helicopter) has been established and is shown in Table 4. Several of the components such as gears, transistors, and assorted hardware for the system are purchased at quantity prices, and their cost for the maximum 100 units shown is essentially fixed. This fixed price is $310. When purchased at quantity prices, the remaining components of the system substantially reduce the per-unit cost of the system. In examination of the curve, it would appear that the unit cost of the system approaches $1,300 as a limit. This component-cost analysis is based on quoted prices for all major cost items and is accurate to within 5 per cent. Table 4 is a tabulation of the cost of components that are shown in the figure on page 5. It should be emphasized that this cost analysis does not include labor and assembly cost.

TABLE 4
ESTIMATED COMPONENT COST

Number of Units	Unit Price of Components
2	$1860
5	$1650
10	$1520
20	$1450
50	$1380
100	$1340

8.0 FLIGHT TEST DATA

The helicopter vibration analyzer was flight tested on two occasions. The first flight test was conducted from 5 to 9 January 1959. This test was conducted prior to a satisfactory calibration of the instrument and was intended primarily to establish quantitative results and to determine the general feasibility of the instrument. The results of this test were satisfactory. The second flight test was conducted during the period 11 to 18 September 1959. The instrument was fully calibrated during this period, and the results of this series of tests are presented in Table 5.

The objectives of the second test program were to establish the operating characteristics of the instrument, to determine satisfactory locations for the vibration pickups, to ascertain the vibration characteristics of the H-21 helicopter, to establish "provisional" vibration limits for the alarm system, and to determine a satisfactory installation procedure.

The operation of the instrument was satisfactory throughout the test period. The quantitative response of the instrument to a vibration level corresponded to the subjective response of both passengers and pilots. It was observed that the vibration was most closely related to collective stick displacement. Flare in the powered landing was the maneuver which appeared to result in the highest levels of vibration. Pilot technique and weather conditions were also contributing factors to the vibration characteristics of the helicopter.

Several locations for the pickups were investigated. There was a distinct difference in reading between a pickup located in the forward portion of the cabin and one located aft in the vicinity of the central transmission. The precise location of the pickups within any one region (forward or aft) was not in itself especially critical provided that the locations were on principal items of structure such as frames, beams, cargo deck plates, etc.

During flight number one, tests one through eight, both pickups were located on the electronic-equipment racks immediately aft and to the left of the pilot's compartment. In flight number two, the pickups were interchanged. During the remainder of the flight tests, the forward pickup was located on the third electronic-equipment rack from the bottom near the main vertical support, and the aft pickup was located on the right side of the helicopter on a horizontal stringer in the central transmission compartment.

As a result of a recently conducted examination of the flight test program, the vibration acceleration limits shown in Table 6 are recommended for the H-21 helicopter.

TABLE 5
FLIGHT TEST VIBRATION DATA, H-21 HELICOPTER

Flight No.	Test No.	Peak Acceleration (g) Pickup Identification 3F*	2F	1F	1A**	2A	3A	Conditions
1	1	.000	.030	.000	.000	.022	.076	Gnd. runup, 10-min. warmup, 2000 r.p.m.
	2	.140	.032	.015	.021	.040	.220	Airborne, 2500 r.p.m., 75 knots.
	3	.150	.053	.015	.021	.040	.260	Airborne, 2500 r.p.m., 75 knots.
	4	.140	.045	.017	.021	.035	.210	Airborne, 2500 r.p.m., 75 knots.
	5	.130	.034	.017	.021	.030	.210	Airborne, 2500 r.p.m., 75 knots.
	6	.100	.034	.015	.019	.024	.150	Hovering, in-gnd. effect, 2500 r.p.m.
	7	.140	.029	.020	.016	.024	.120	Hovering, in-gnd. effect, 2400 r.p.m.
	8	.190	.036	.022	.026	.052	>.300	Hovering, in-gnd. effect, 2700 r.p.m.
2	1	.230	.031	.020	.017	.029	.165	Alt. 1500 ft., 2400 r.p.m., 80 knots.
	2	.190	.042	.025	.018	.029	.150	Alt. 1500 ft., 2400 r.p.m., 60 knots.
	3	.240	.036	.022	.021	.037	.150	Alt. 1500 ft., 2500 r.p.m., 40 knots.
3								Flight cancelled.
4	1	.062	.066	.013	.010	.052	.115	Gnd. runup, 5-min. warmup, 1600-2000 r.p.m.
	2	.120	.055	<.010	.015	.050/.090	.052	Gnd. runup, 10-min. warmup, 2000 r.p.m.
	3	.062	.055	.013	.015	.060/.080	.064	Low fwd. speed and hovering, 2500 r.p.m.
	4	.180	.060/.100	.016	.021	.060/.110	.080/.120	Straight and level, 2500 r.p.m., 80 knots.
	5	.190	.055	.020	.021	.046	.085	Straight and level, 2500 r.p.m., 80 knots.
	6	.180	.040/.080	.016	.024	.060/.070	.085	Straight and level, 2500 r.p.m., 80 knots.
	7	.190	.066	.016	.024	.046	.120	Straight and level, 2500 r.p.m., 80 knots.
5	1	.000	.000	.000	.000	.000	.000	Instrumentation null.
	2	.000	<.010	.000	<.010	<.010	<.040	Gnd. runup, 1-min. warmup, 1600-2000 r.p.m.
	3	.045	.040/.070	.010	.010	.040	.085	Gnd. runup, 10-min. warmup, 2000 r.p.m.
	4	.140	.076	.017	.019	.070	.065	Running takeoff and climb.
	5	.150	.055	.017	.019	.066	.060	Turning climb, 60 knots.
	6	.140/.170	.060/.100	.017/.022	.024	.060/.090	.085/.125	Straight and level, 2500 r.p.m., 70-80 knots.
	7	.170	.025/.040	.014	.024	.060/.080	.085/.125	Straight and level, 2500 r.p.m., 70-80 knots.
	8	.175	.025/.040	.014	.024	.057	.085/.125	Straight and level, 2500 r.p.m., 70-80 knots.
	9	.170	.025/.040	.016	.024	.060/.100	.085	Straight and level, 2500 r.p.m., 70-80 knots.
	10	.140	.025	.016	.050	.062	.105	Powered glide, 2500 r.p.m., 100 knots.
6	1	.000	.055	.000	.000	.040	.040	Gnd. runup, 5-min. warmup, 2000-2500 r.p.m.
	2	.060	.015	>.010	.013	.040	.060	Hovering, in-gnd. effect, 2500 r.p.m.
	3	.120	.042	.011	.017/.022	.052	.050	Climb, 2500 r.p.m., 60 knots.
	4	.130	.024	>.010	.020	.060/.070	.060/.100	Cruise, 2500 r.p.m., 80-90 knots.
	5	.140	.020	.011	.017/.035	.060/.070	.070/.110	Cruise, 2500 r.p.m., 80-90 knots.
7	1	.045	.024	>.010	.024	.038	.080/.150	Gnd. runup, 10-min. warmup, 2000 r.p.m.
	2	.170	.032	.022	.024	.044	.120	Climb, 2500 r.p.m., 60 knots.
	3	.150	.066	.022	.024	.052	.120	Autorotation landing, smooth.
	4	.190	.055	.022	.020	.070	.220	Autorotation landing, hard.
	5	.170	.066	.015	.021	.040	.100	Autorotation landing, hard.
	6	.075	.014	.025	.026	.050/.080	.120/.180	Straight and level, 2500 r.p.m., 80 knots.
	7	.075	.043	.022/.230	.043	.057	.120	Straight and level, 2500 r.p.m., 80 knots.
	8	.070	.014	.022	.030	.046	.100	Straight and level, 2500 r.p.m., 80 knots.
8	1	.000	.000/.034	.010	.021	.022	.120	Gnd. runup, 10-min. warmup, 2000 r.p.m.
	2	.230	.020/.060	.025	.021	.052	.085	Taxi, 2000 r.p.m.
	3	.240/.260	.040/.060	.033	.024	.040	.085	Straight and level, 2500 r.p.m., 80-90 knots.
	4	.190/.270	.042	.028	.024	.046	.065	Straight and level, 2500 r.p.m., 80-90 knots.
	5	.230	.034	.028	.033	.040	.085	Straight and level, 2500 r.p.m., 80-90 knots.

* F - forward rotor
** A - aft rotor

TABLE 6
PRESCRIBED VIBRATION ACCELERATION LIMITS, H-21 HELICOPTER

Analyzer Amplifier Relay Adjustment	Harmonics (g)		
	1/rev.	2/rev.	3/rev.
Low	.050	.065	.200
High	.070	.100	.250

9.0 HELICOPTER VIBRATION DATA

This section presents vibration data for the Sikorsky H-19, H-34, H-37; Vertol H-21, H-25; Bell H-13 and XH-40 helicopters (see Figures 6 through 12). These data were recorded during vibration survey and acceptance tests, in general to establish compliance with Specification MIL-H-8501 or deviations thereto. As they were originally received, the data were in the form of amplitude-velocity curves for the main rotor fundamental and several higher harmonics and were recorded at specified locations (cockpit, center of gravity, aft cargo, etc.) and directions (vertical, lateral, and longitudinal).

The form in which the data are presented in this report has been selected as double amplitude versus frequency with a superimposed scale of constant acceleration in g's. Average values of amplitude in the speed ranges of 0-30, 40-85, and 95 to maximum forward speed were established. These speed ranges are representative of transition, cruise, and high-speed flight respectively.

In general, the vibration data were established while the helicopter was flown in uniform rectilinear motion. Maneuvering flight and transient rough air conditions were eliminated. The data were recorded under ideal "laboratory" conditions: a skilled pilot was at the controls and excellent ground maintenance and repair services were available.

Although instances have been cited wherein a helicopter has indicated a lower level of vibration during normal service life, the data recorded during acceptance tests must be considered as indicative of the lowest possible level of vibration for that particular ship.

A variation of the order of ±50 per cent was observed in the amplitude from ship to ship of the same series. This variation is attributed to a difference in component characteristics, assembly, and testing techniques. For this reason considerable care must be taken in interpreting and applying the data, particularly where there were few recorded points. No direct comparison of models from different manufacturers can be made. The differences in testing techniques and in particular the location of sensing elements preclude this possibility.

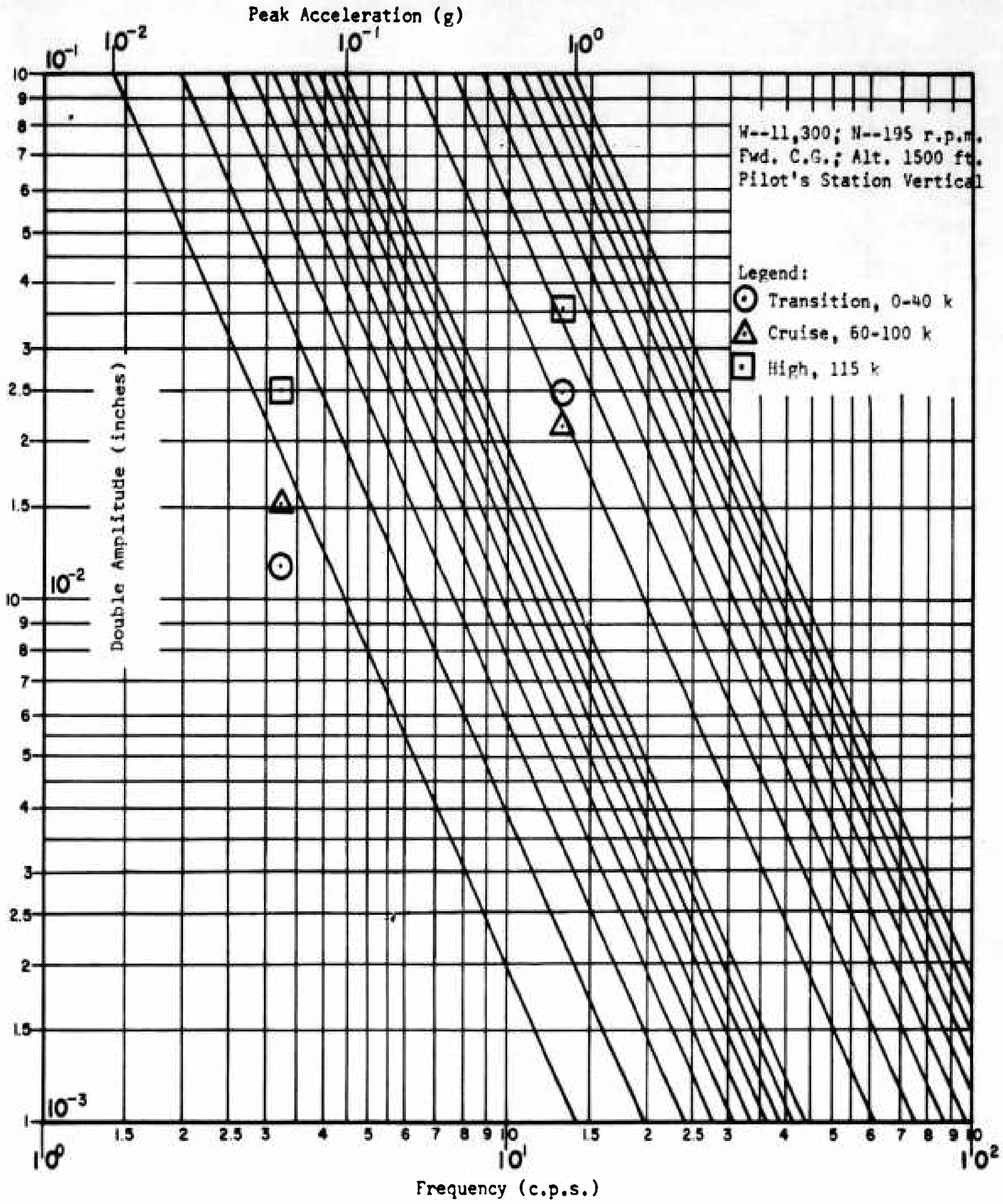


Figure 6a. Vibration Data for the Model H-34 Sikorsky.

-15-

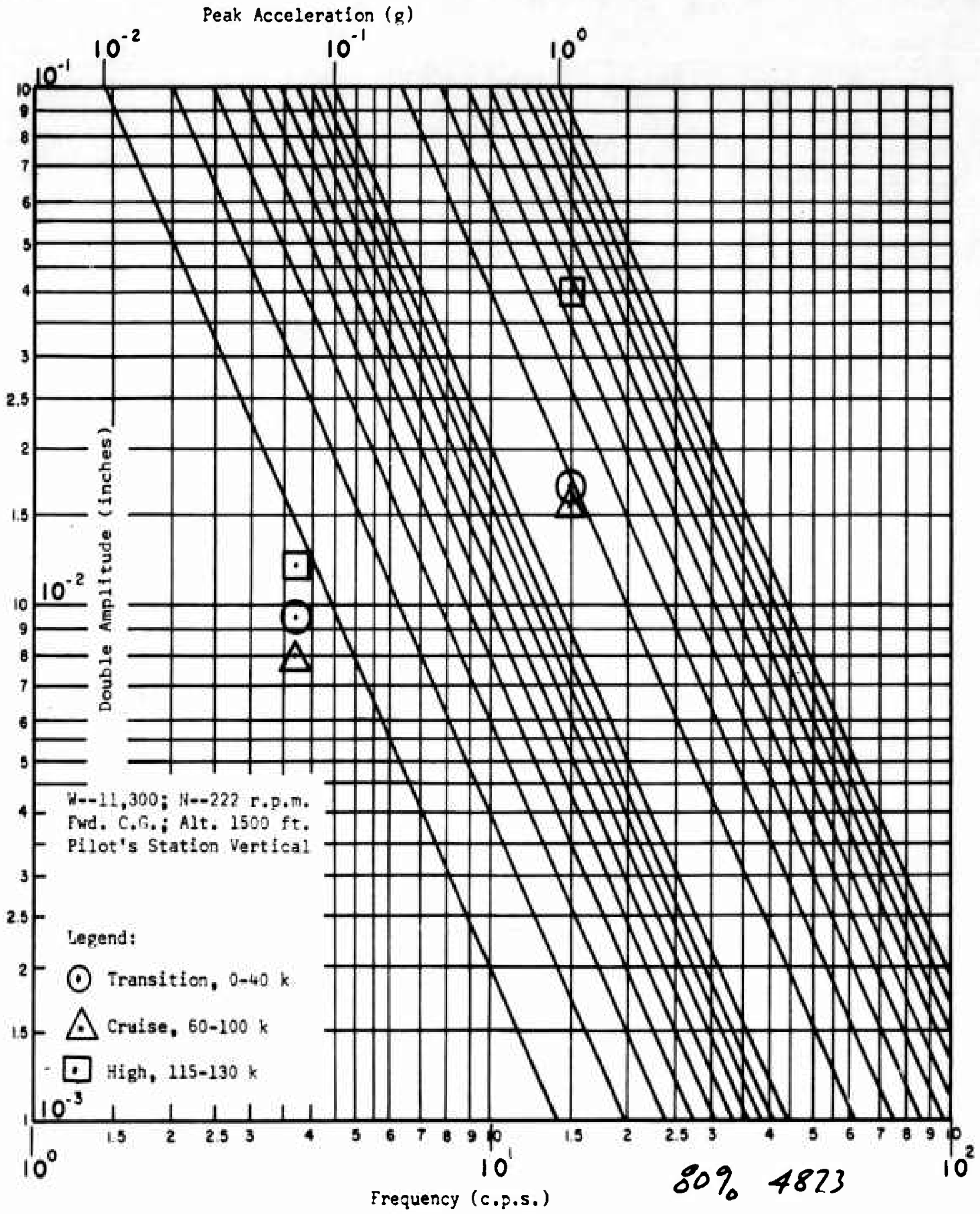


Figure 6b. Vibration Data for the Model H-34 Sikorsky.

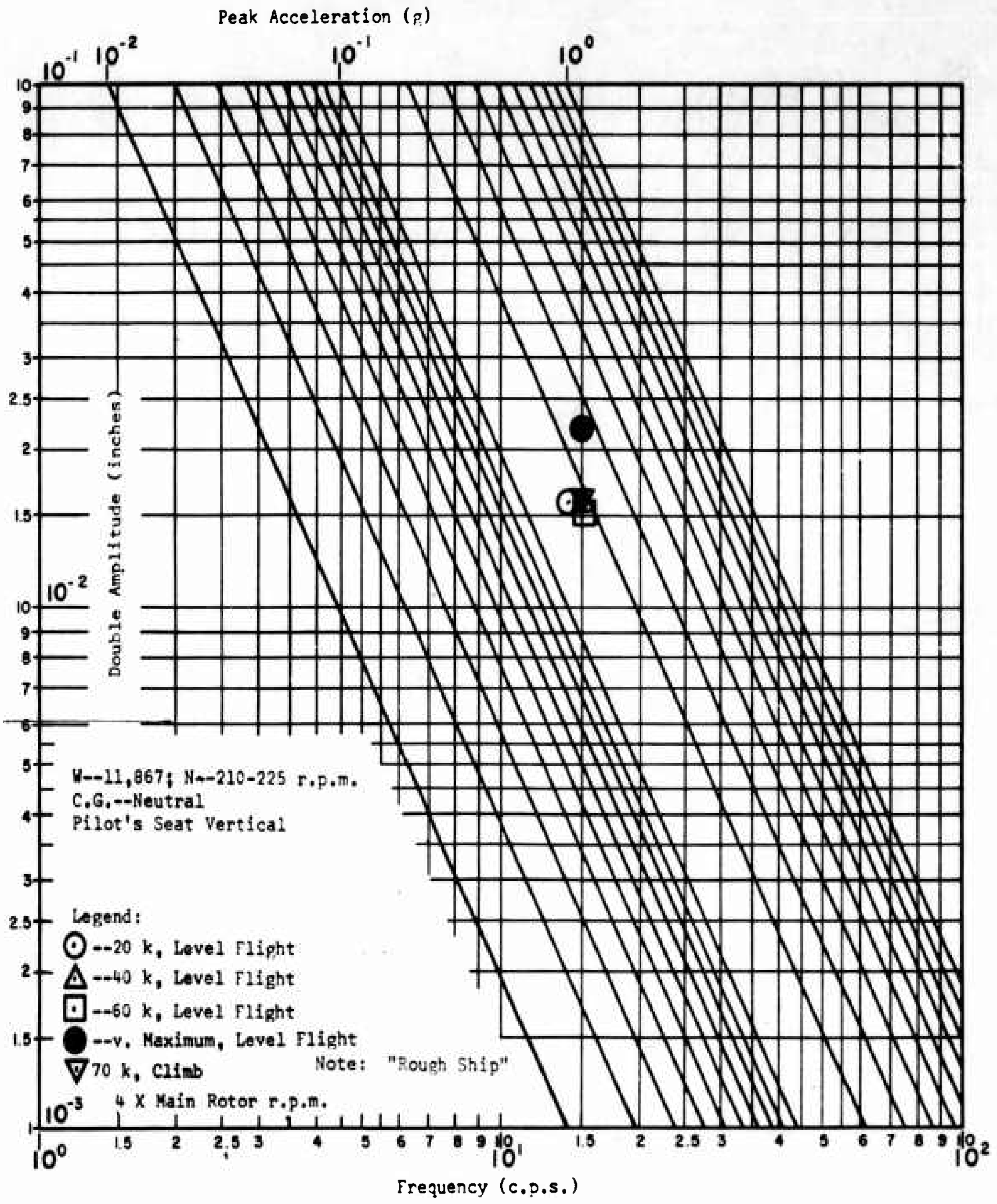
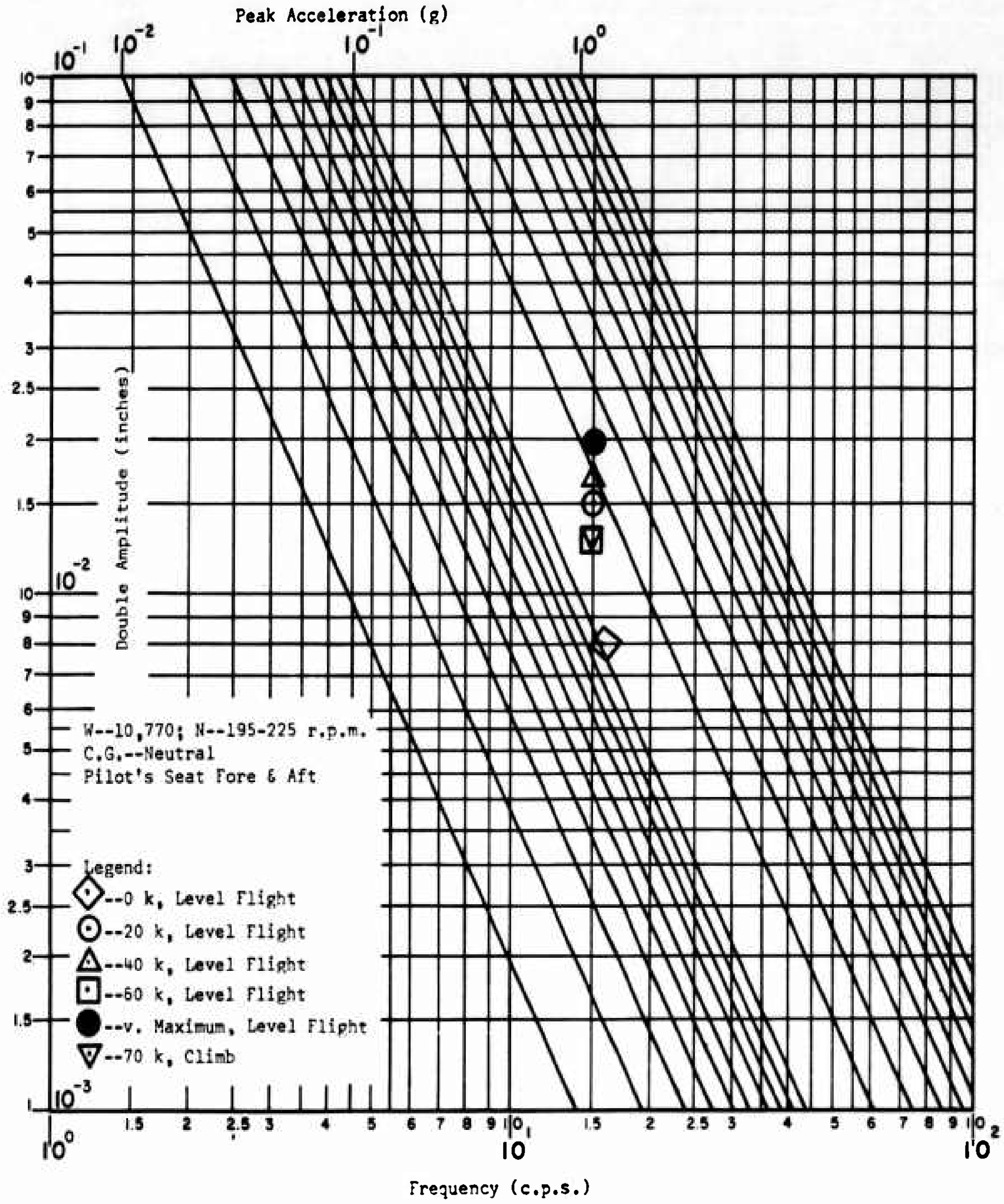


Figure 6c. Vibration Data for the Model H-34 Sikorsky.

-17-



6d. Vibration Data for the Model H-34 Sikorsky.

-18-

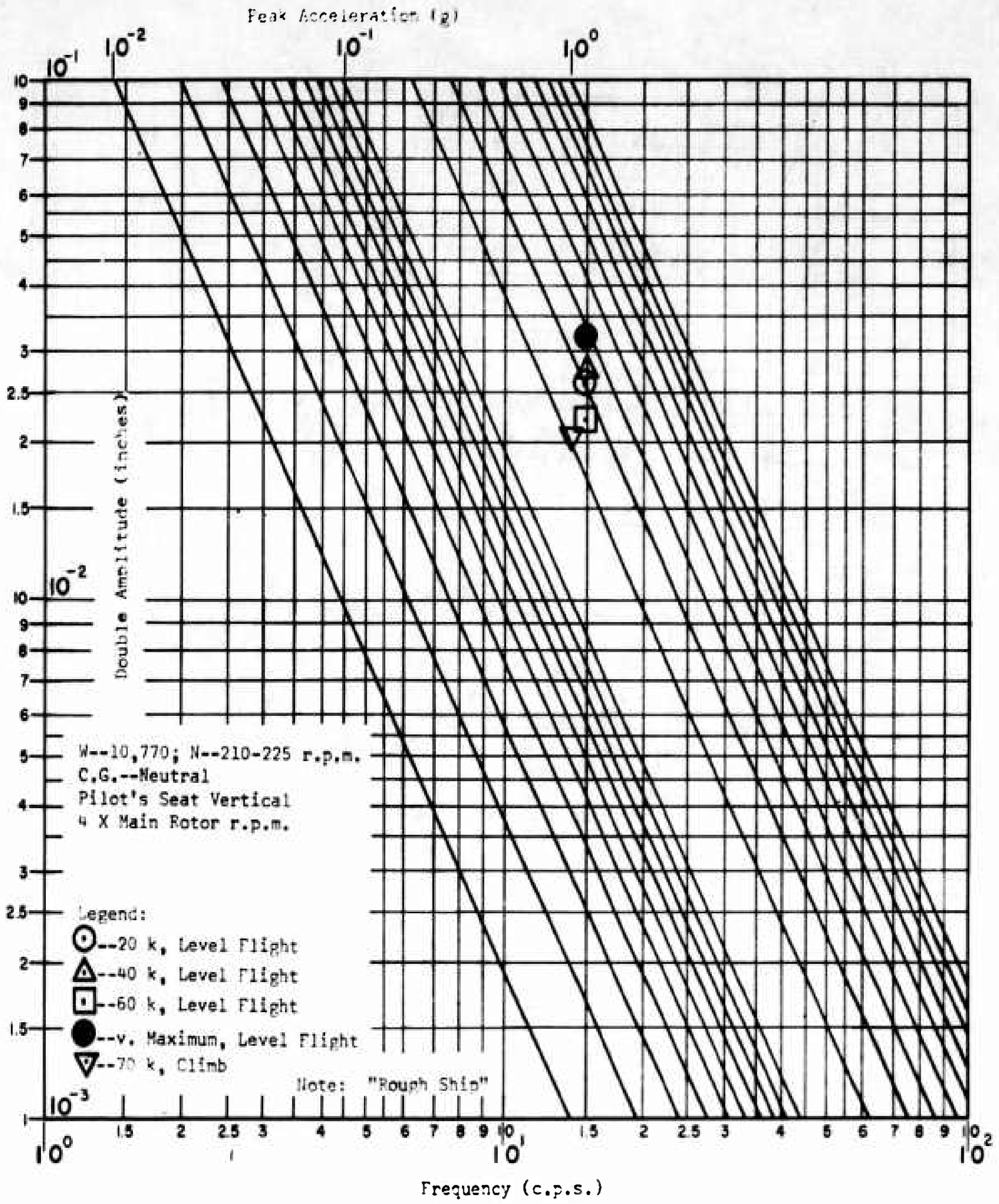


Figure 6e. Vibration Data for the Model H-34 Sikorsky.

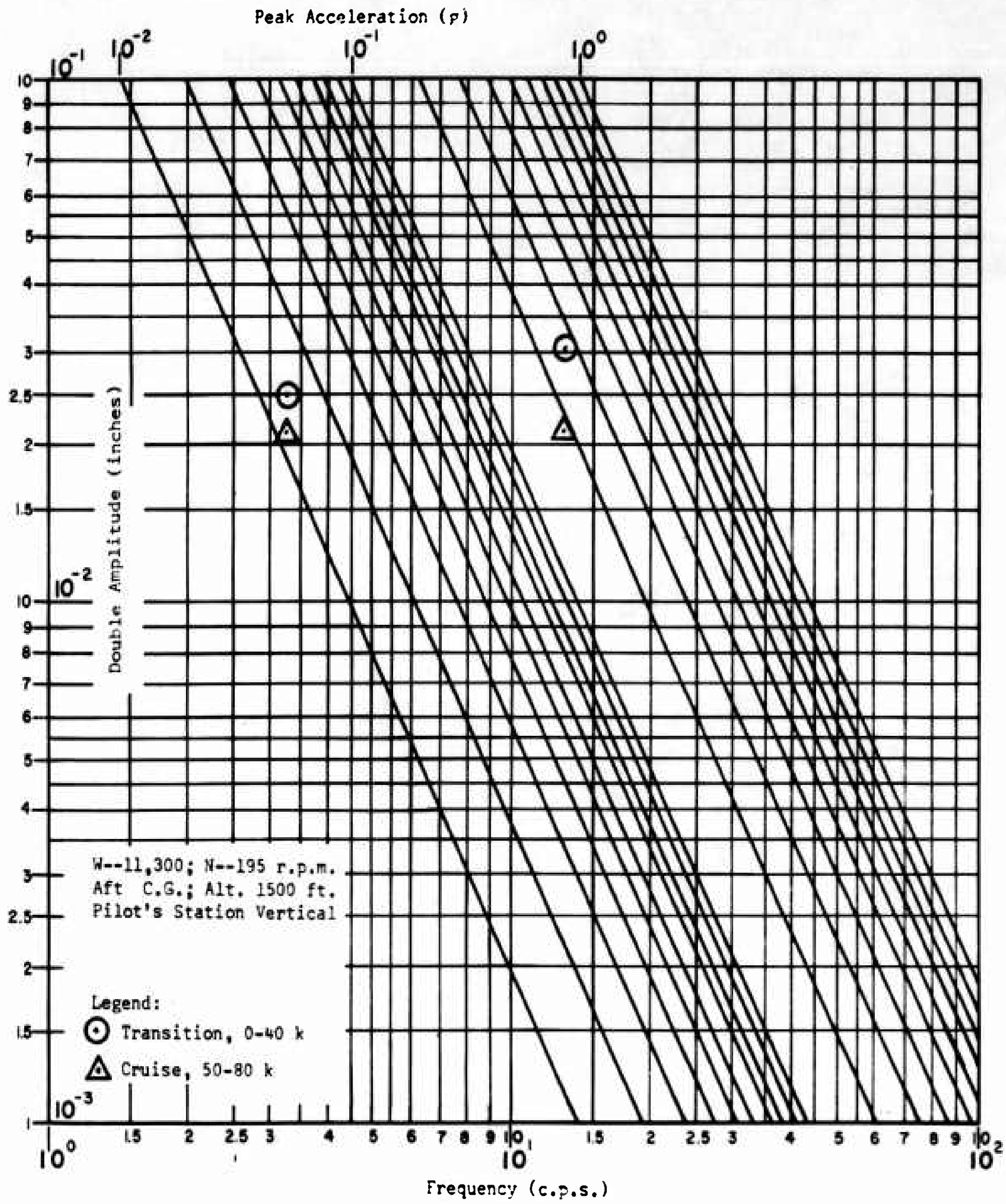


Figure 6f. Vibration Data for the Model H-34 Sikorsky.

-20-

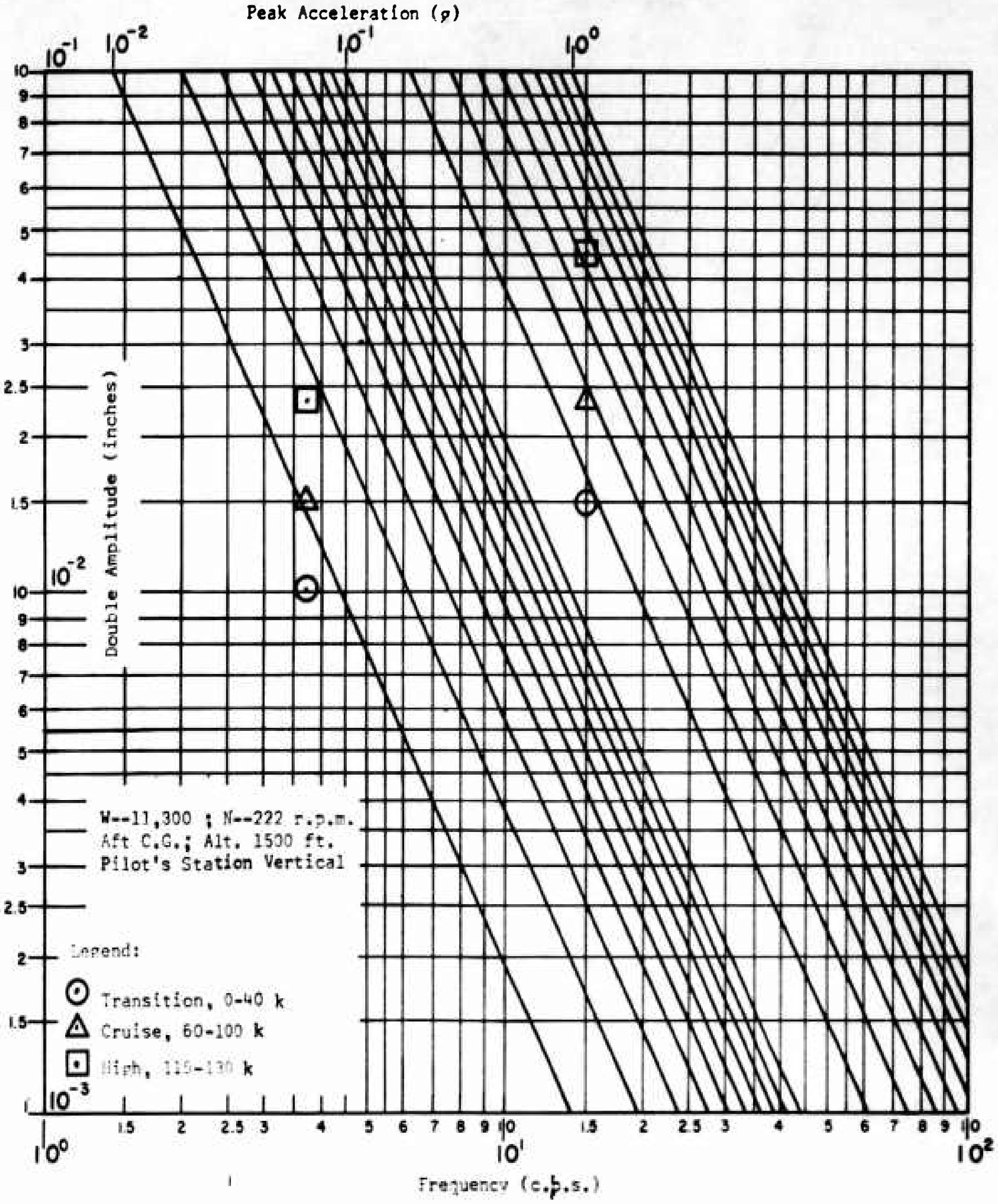


Figure 6g. Vibration Data for the Model H-34 Sikorsky.

-21-

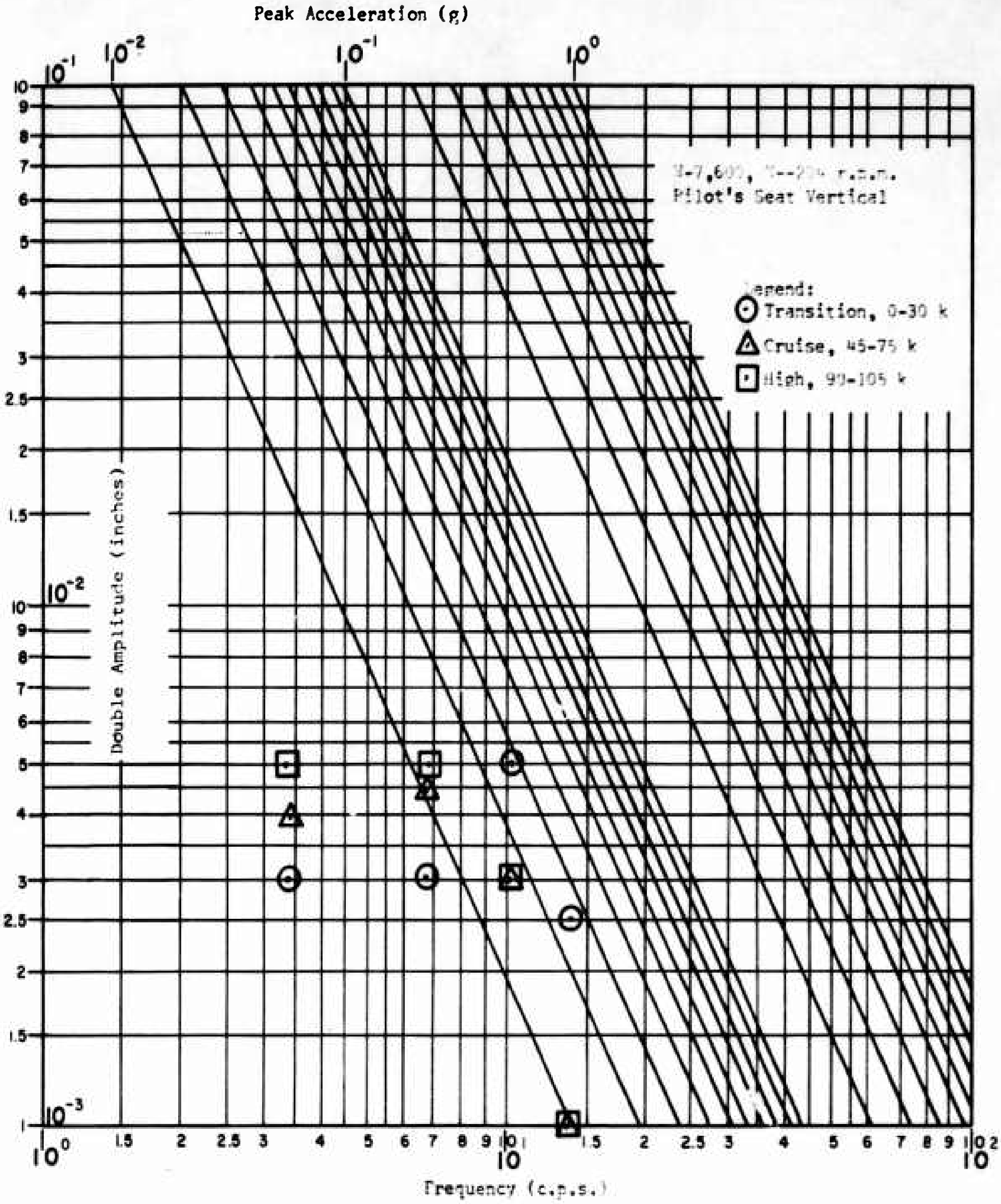


Figure 7. Vibration Data for the Model H-19 Sikorsky.

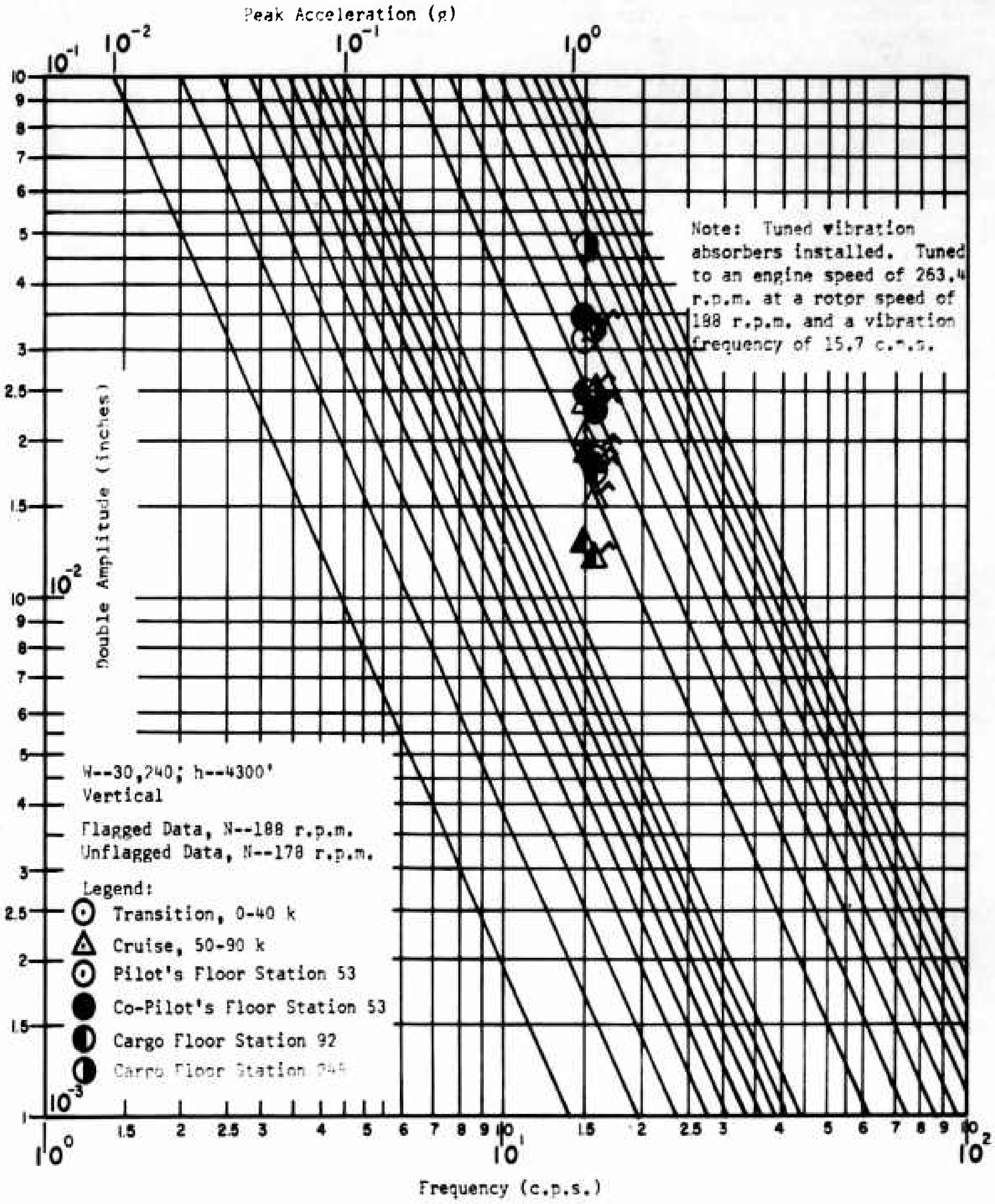


Figure 8a. Vibration Data for the Model H-37A Sikorsky.

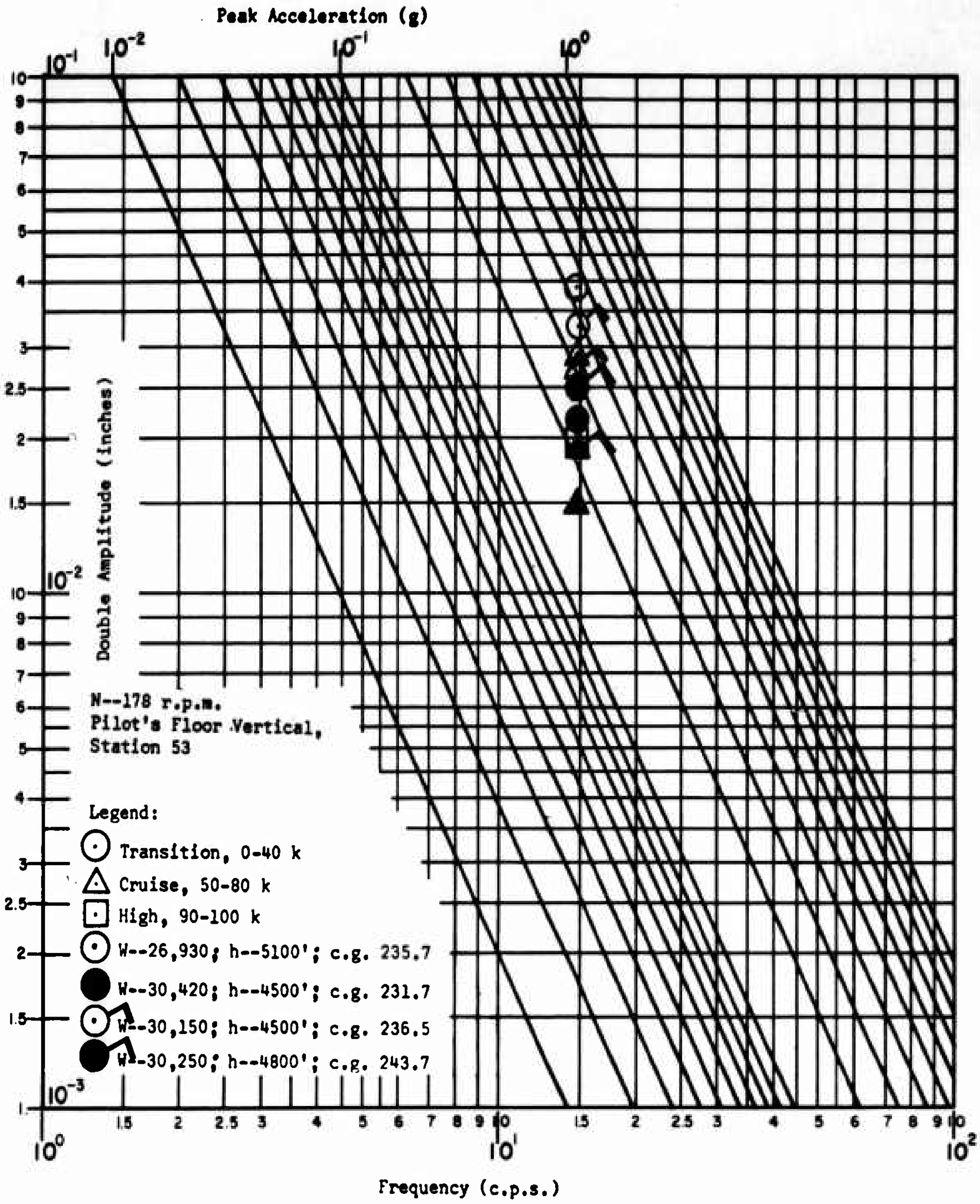


Figure 8b. Vibration Data for the Model H-37A Sikorsky.

-24-

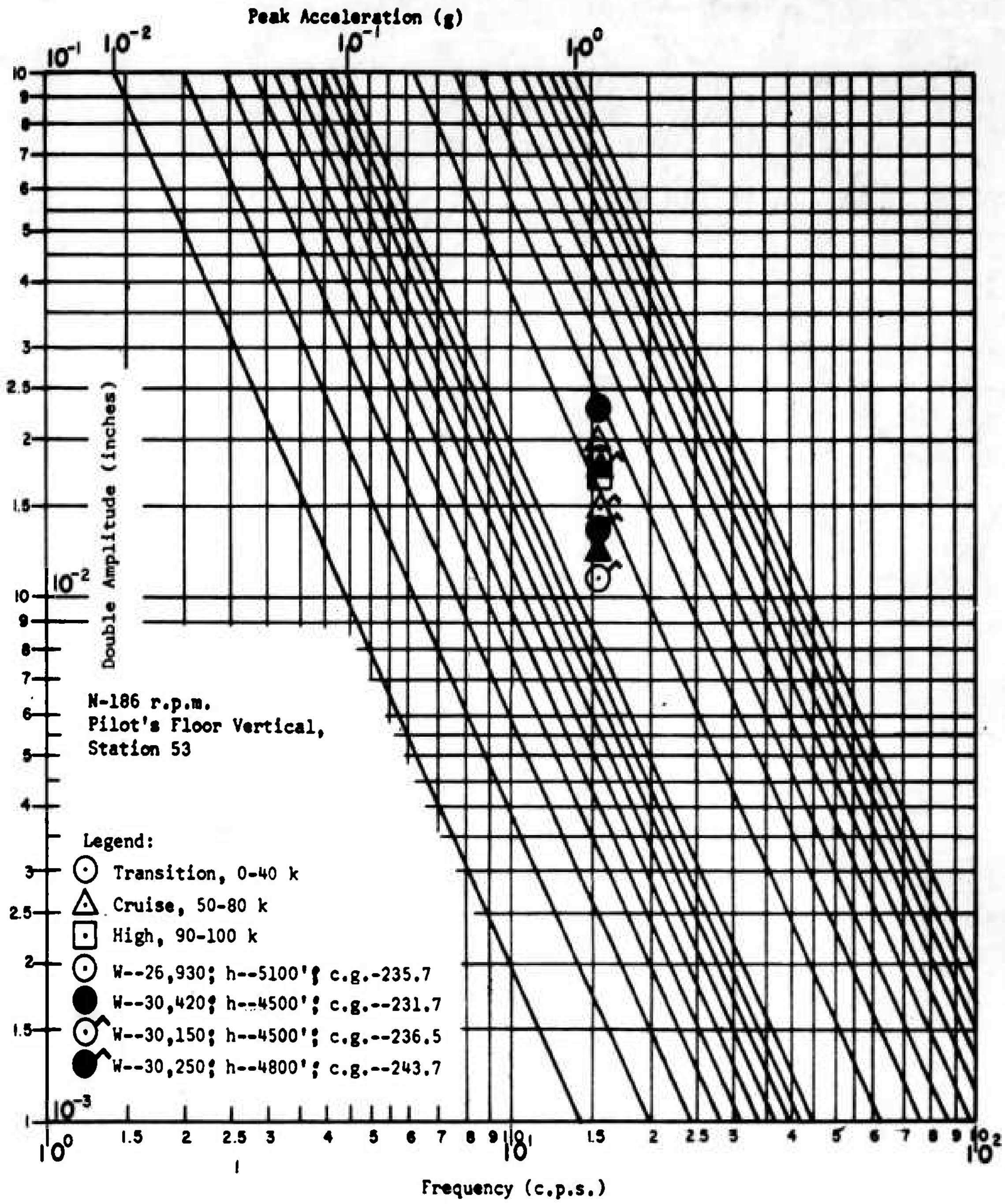


Figure 8c. Vibration Data for the Model H-37A Sikorsky.

-25-

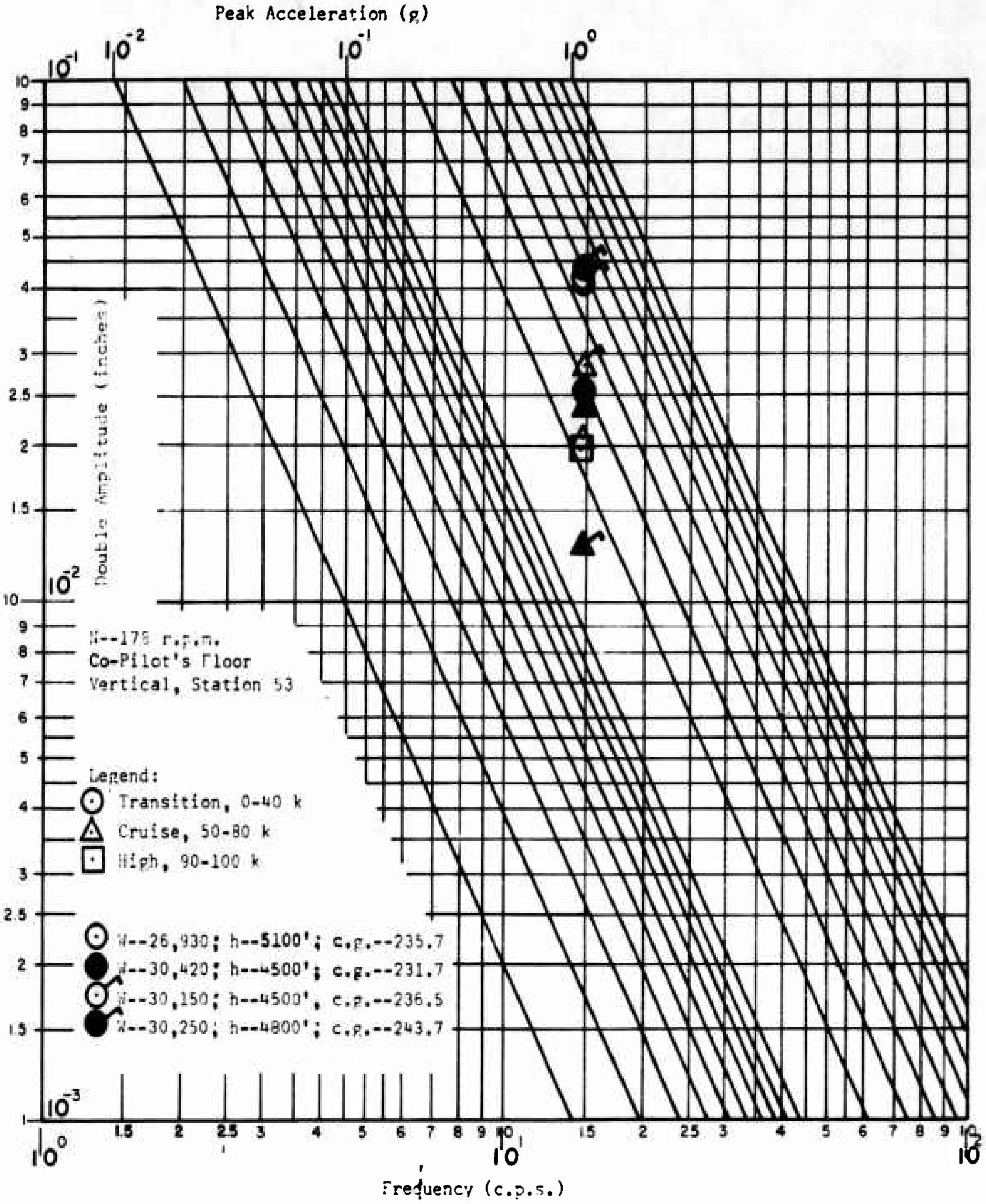


Figure 8d. Vibration Data for the Model H-37A Sikorsky.

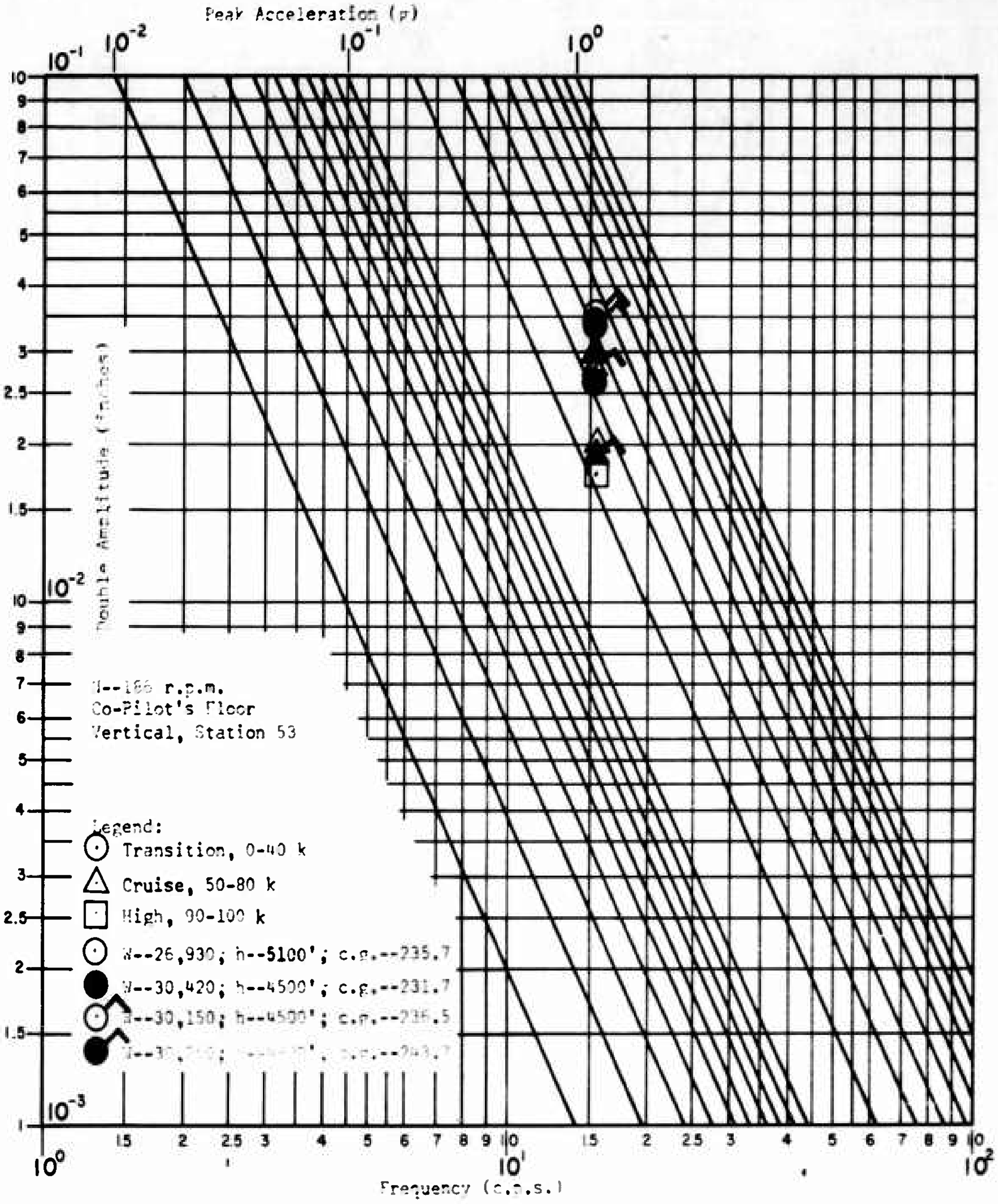


Figure 8e. Vibration Data for the Model H-37A Sikorsky.

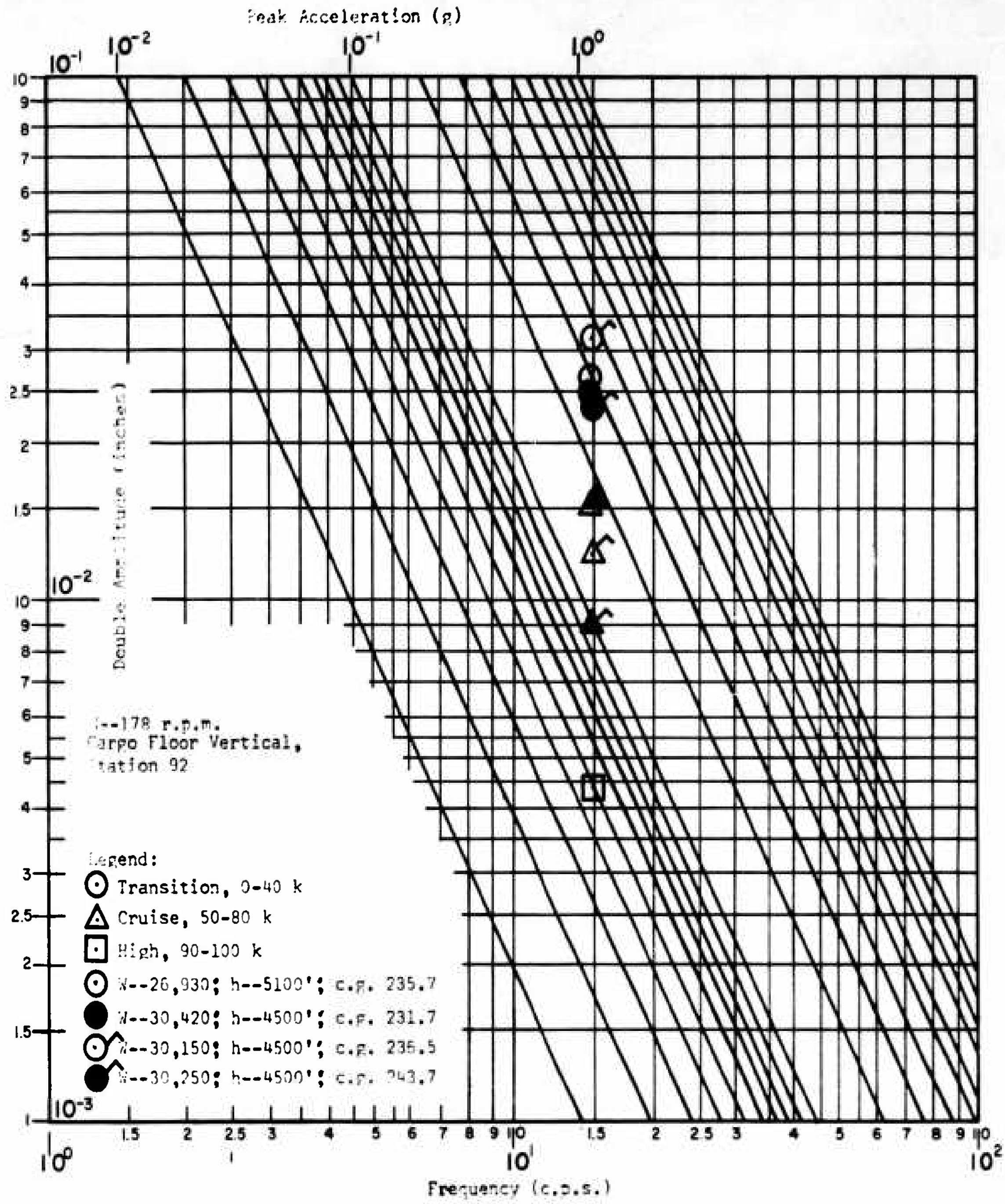


Figure 8f. Vibration Data for the Model H-37A Sikorsky.

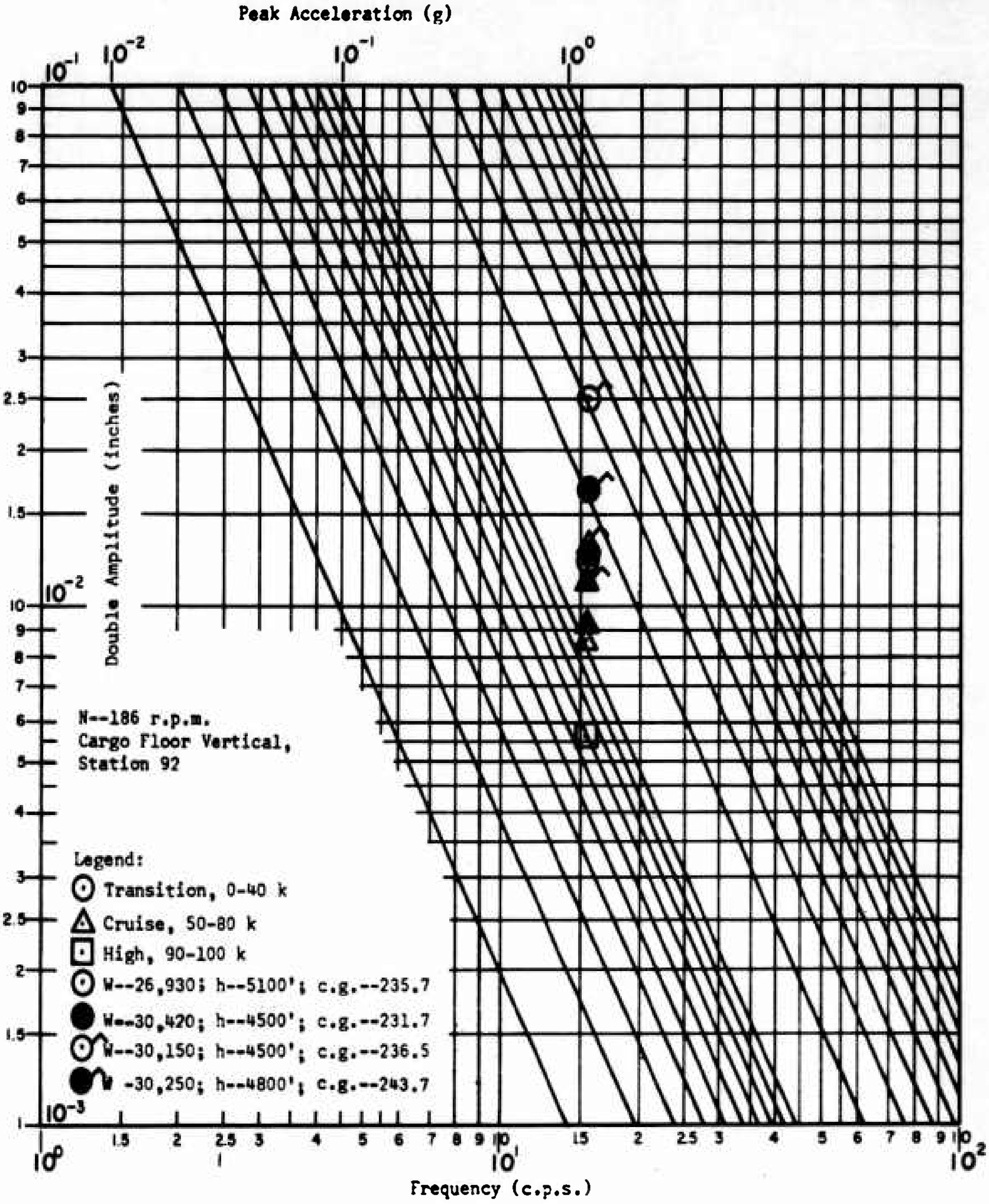


Figure 8g. Vibration Data for the Model H-37A Sikorsky.

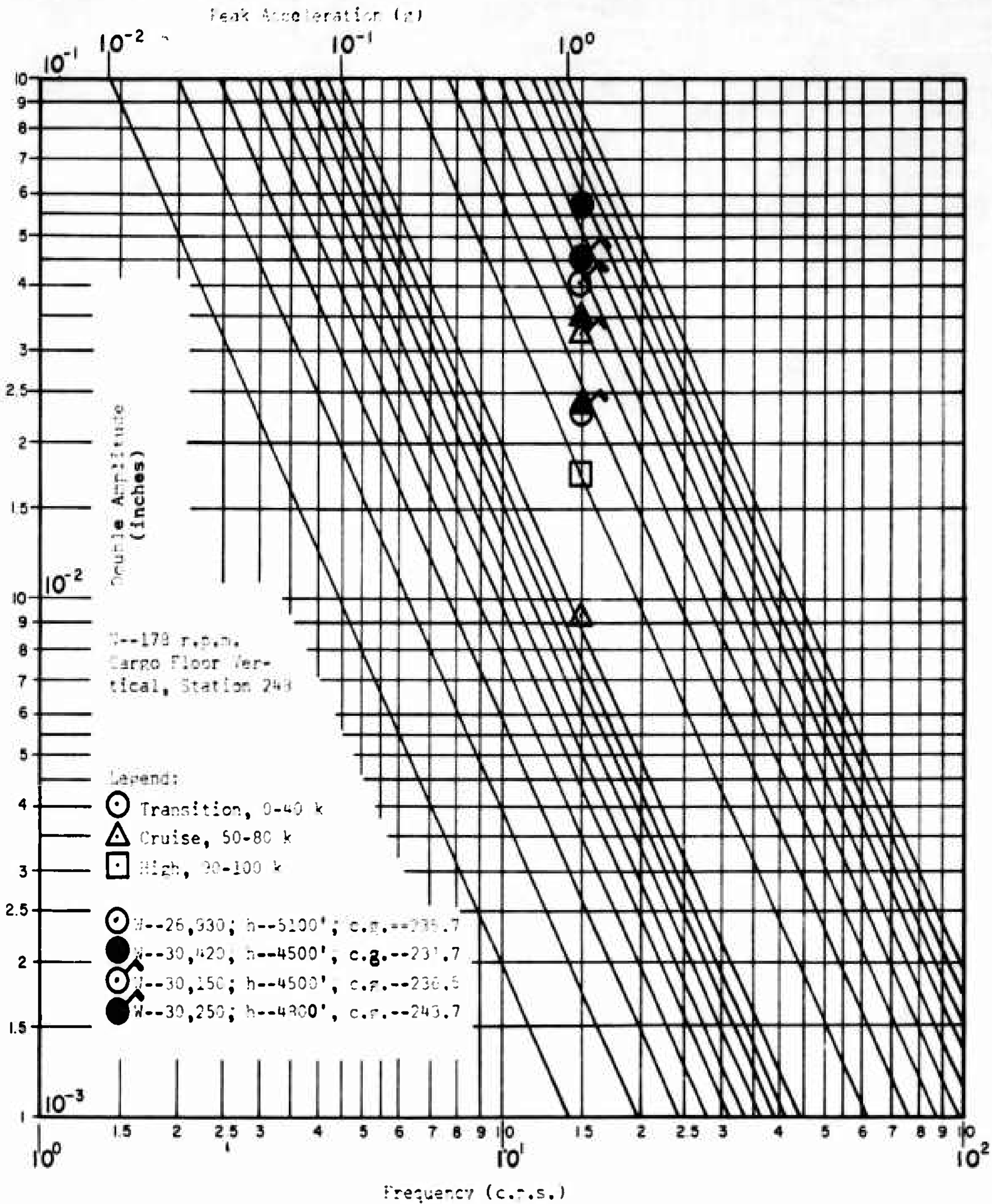


Figure 8h. Vibration Data for the Model H-37A Sikorsky.

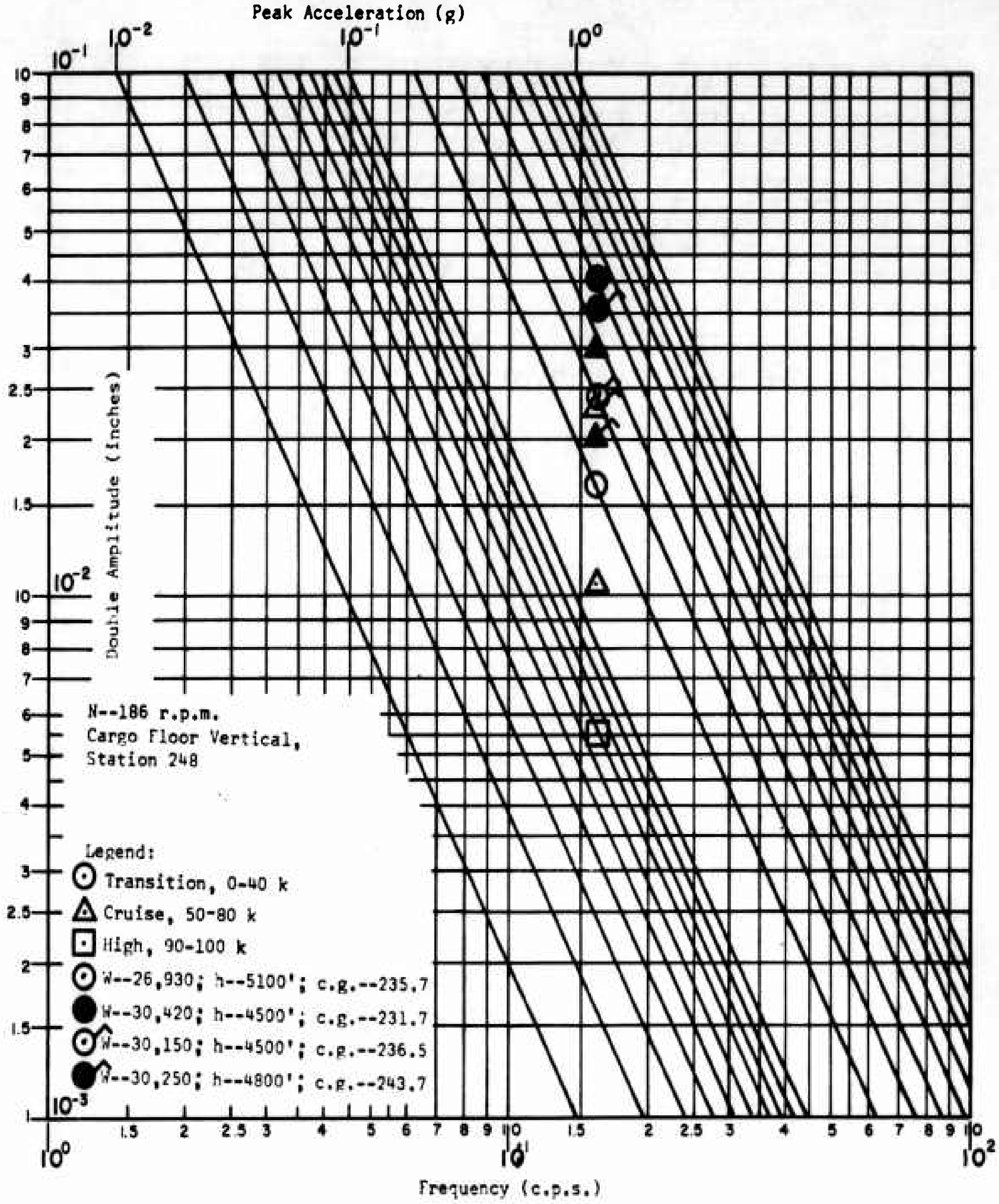


Figure 8i. Vibration Data for the Model H-37A Sikorsky.

-31-

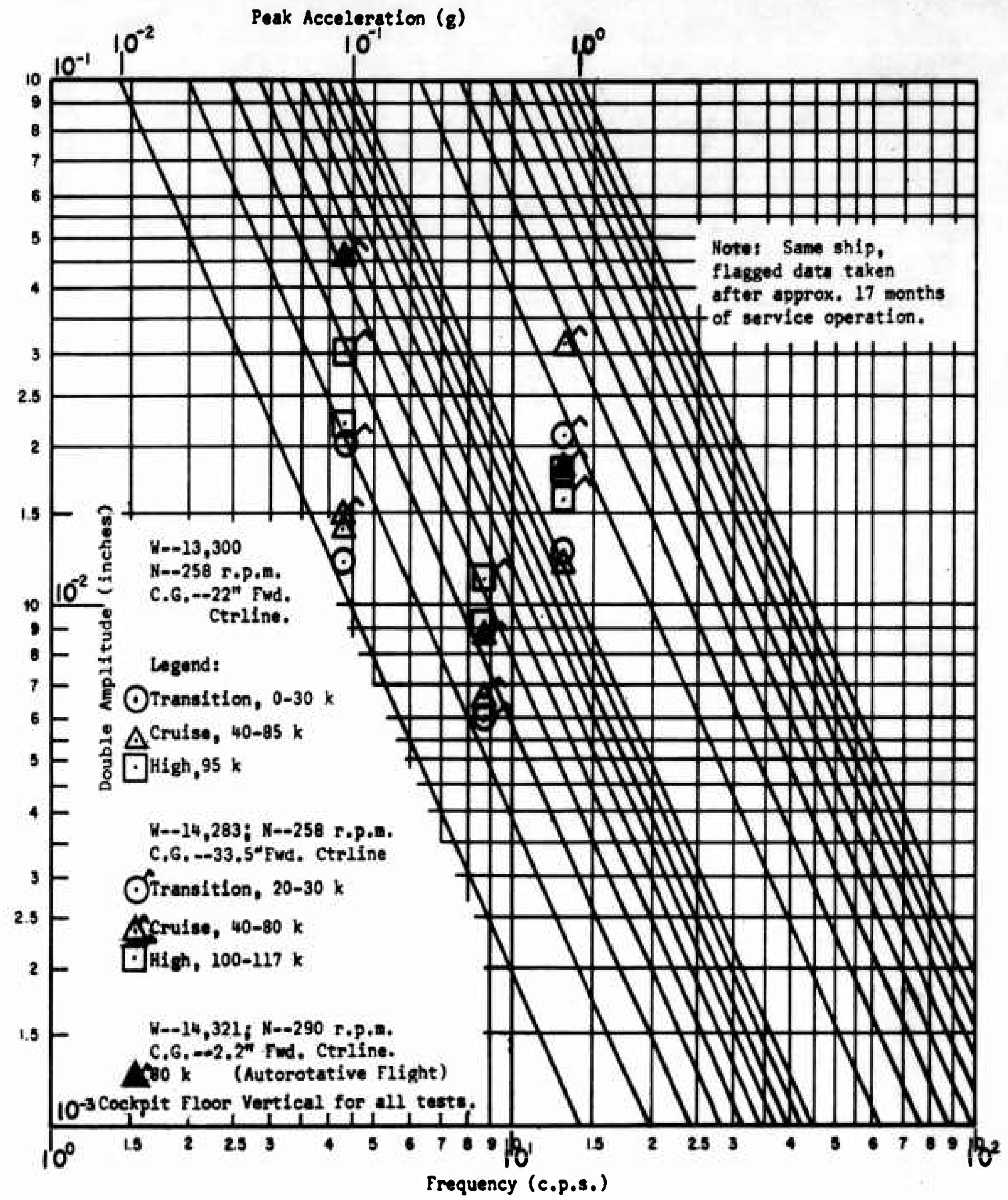


Figure 9a. Vibration Data for the Model H-21 Vertol.

-32-

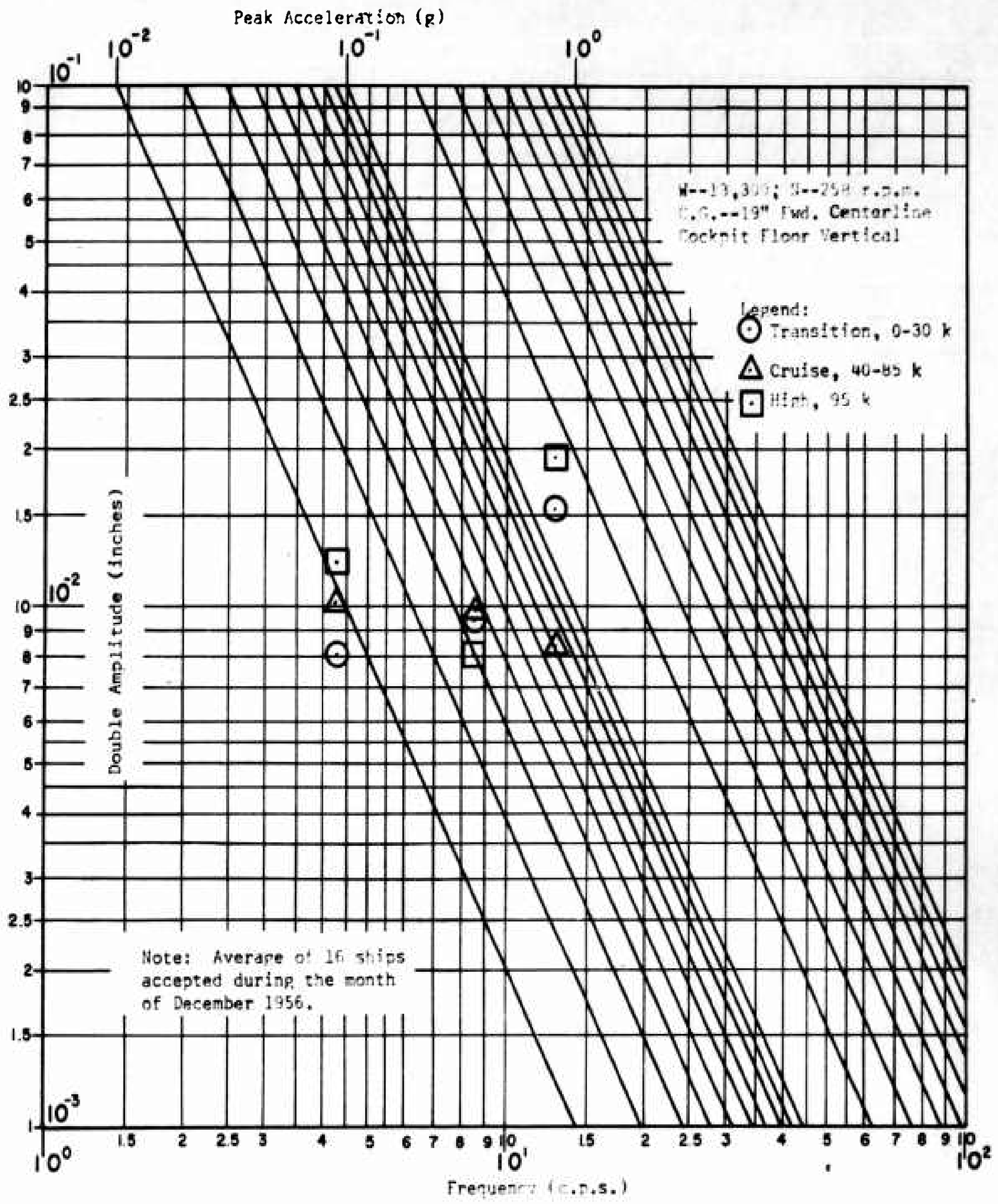


Figure 9b. Vibration Data for the Model H-21 Vertol.

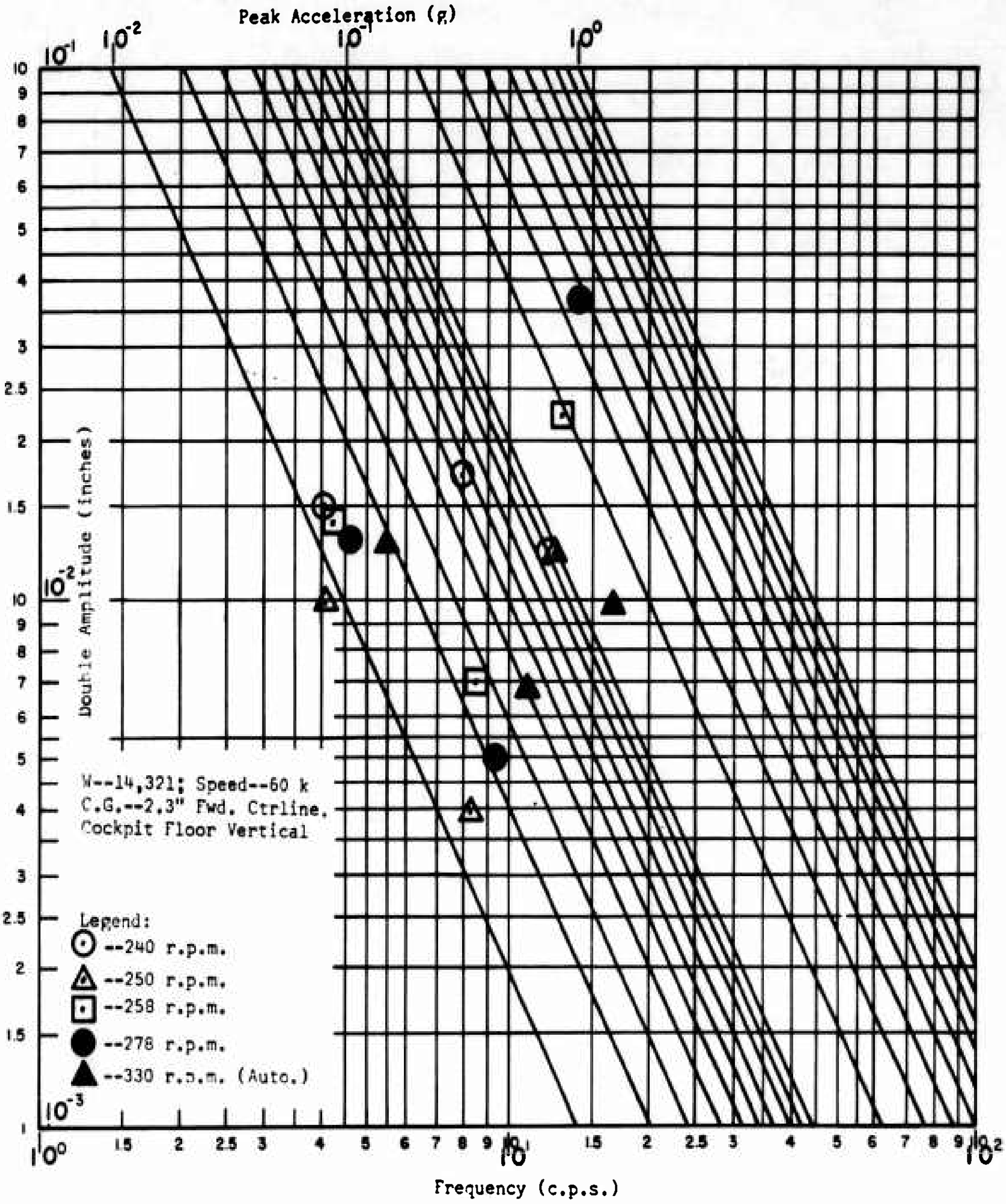


Figure 9c. Vibration Data for the Model H-21 Vertol.

-34-

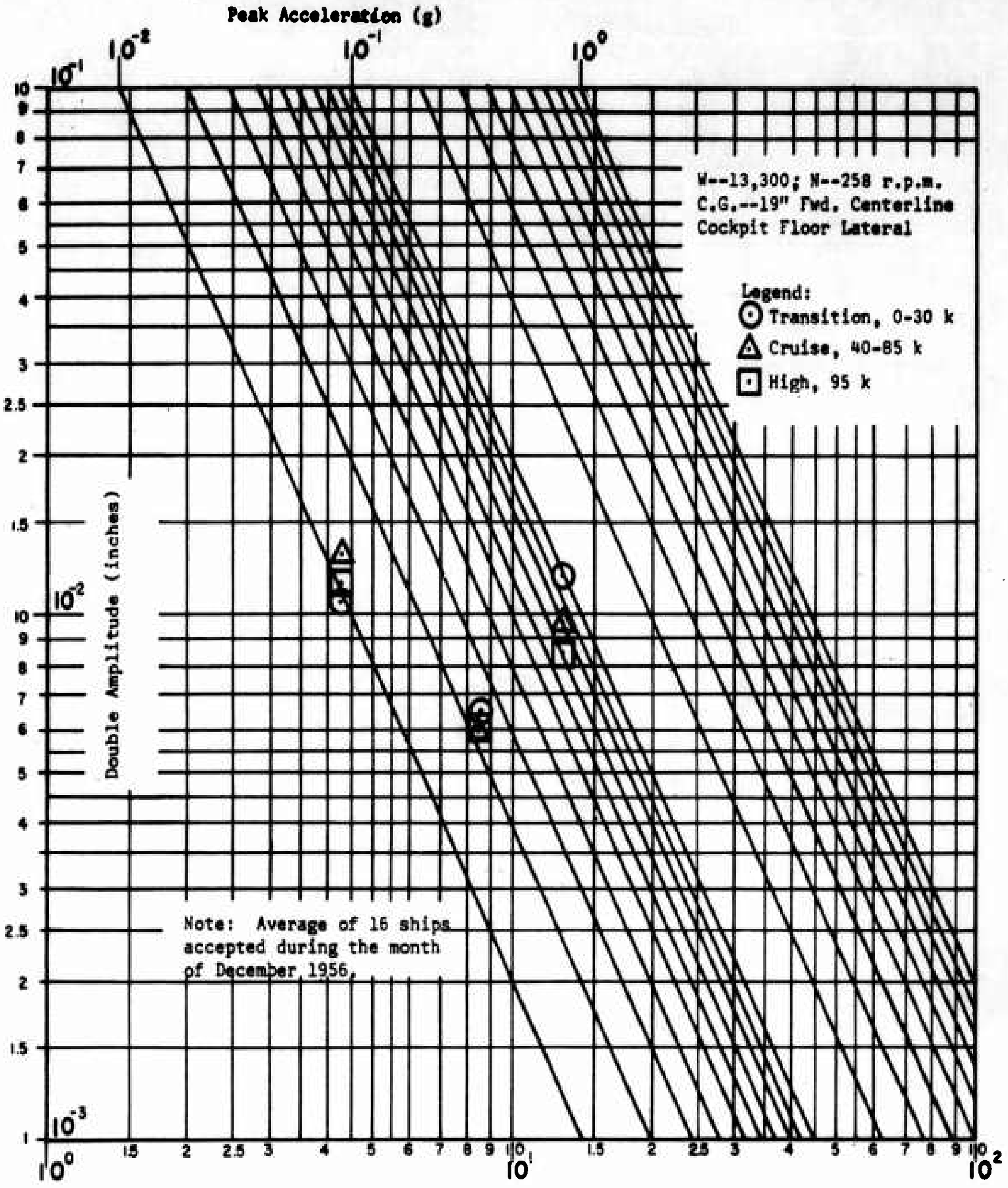


Figure 9d. Vibration Data for the Model H-21 Vertol.

-35-

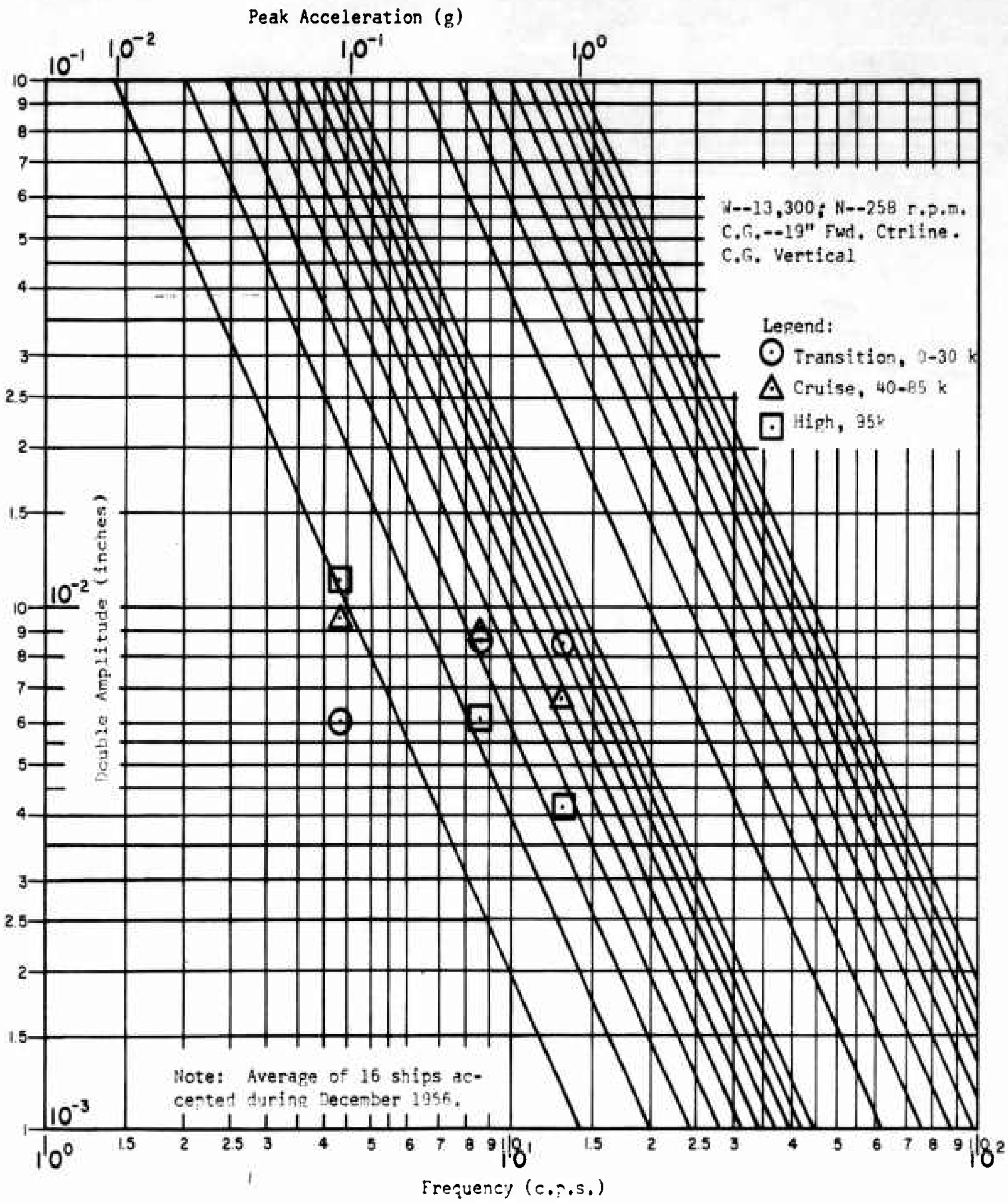


Figure 9e. Vibration Data for the Model H-21 Vertol.

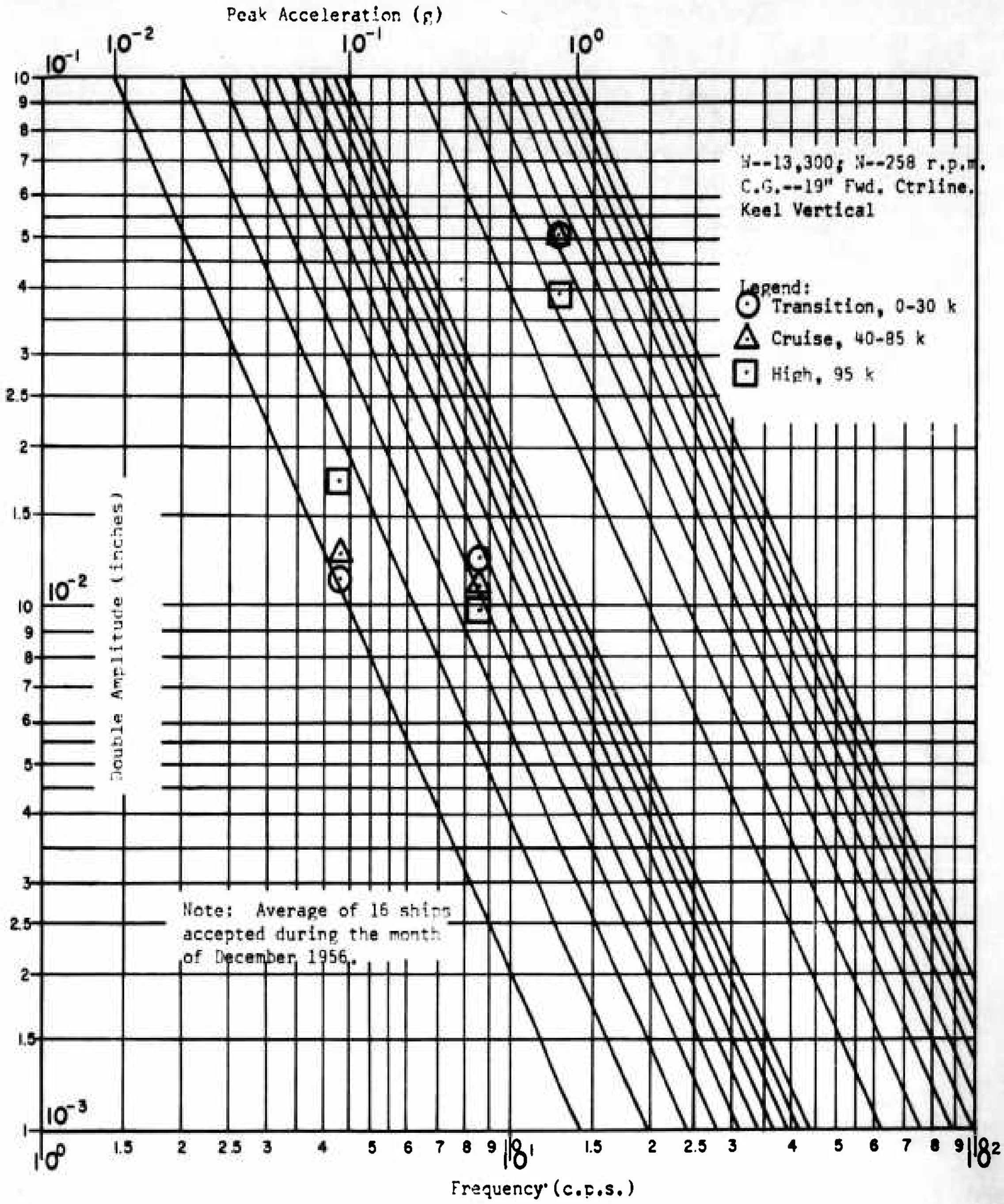


Figure 9f. Vibration Data for the Model H-21 Vertol.

-37-

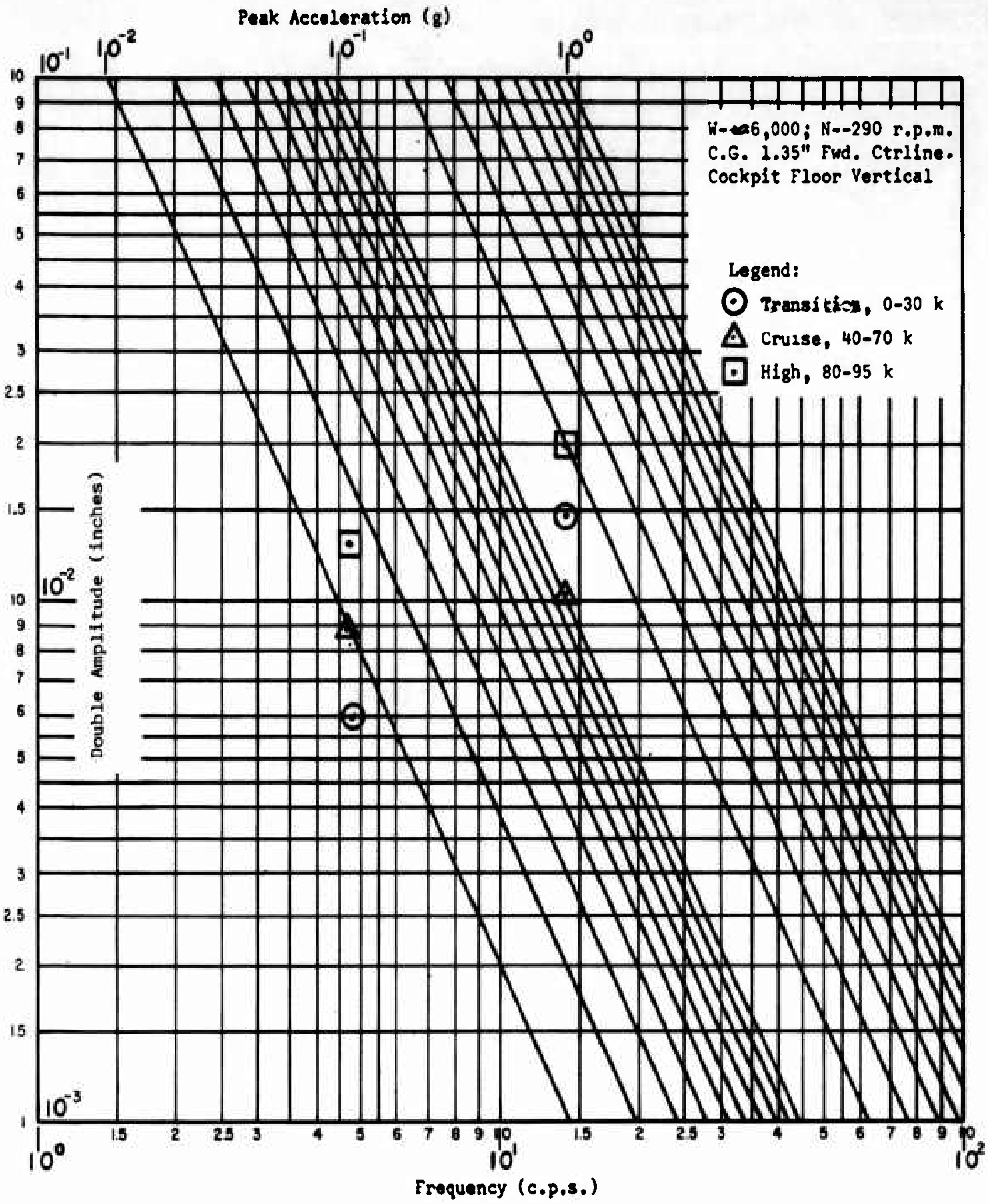


Figure 10. Vibration Data for the Model H-25 Vertol.

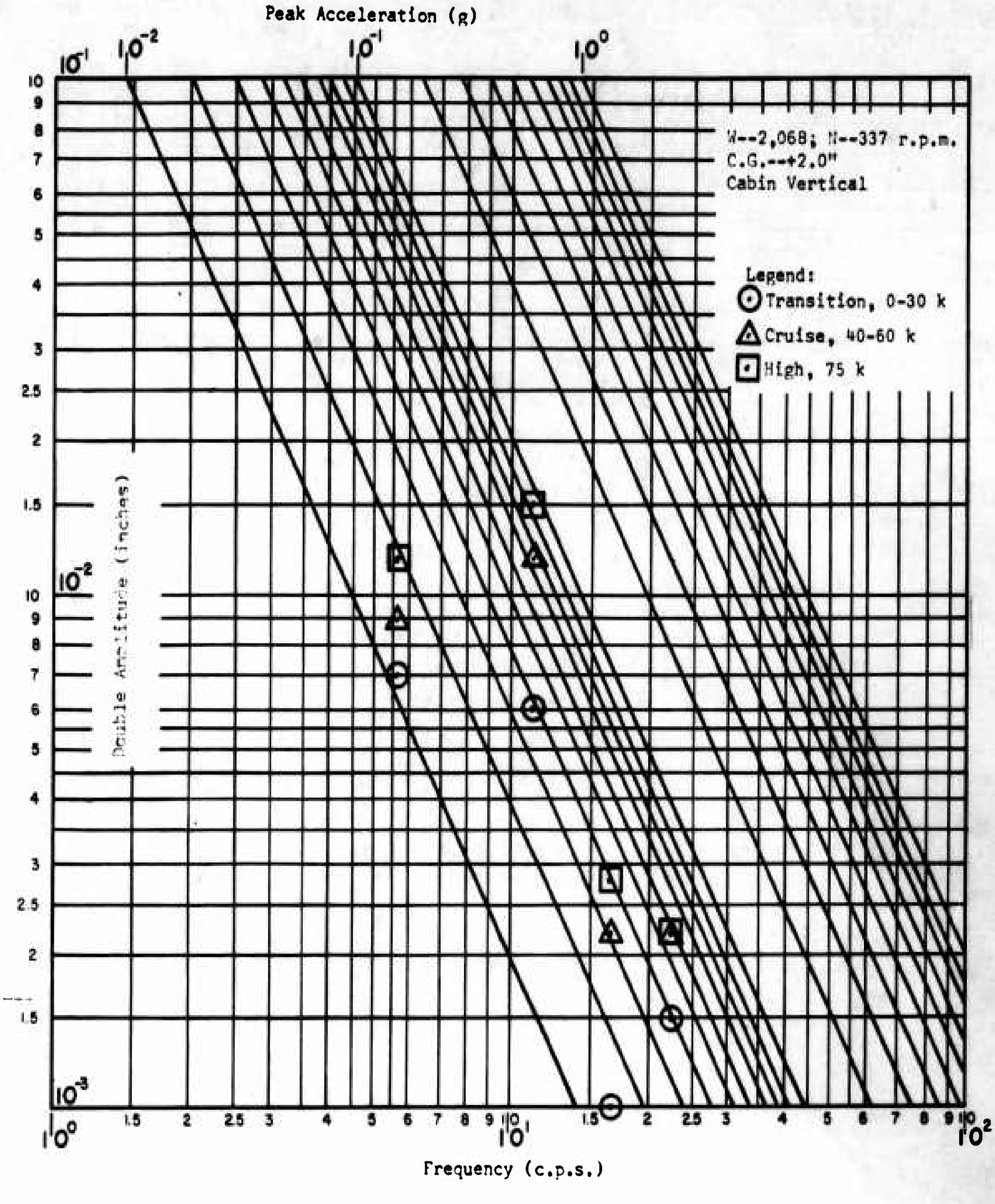


Figure 11. Vibration Data for the Model H-13 Bell.

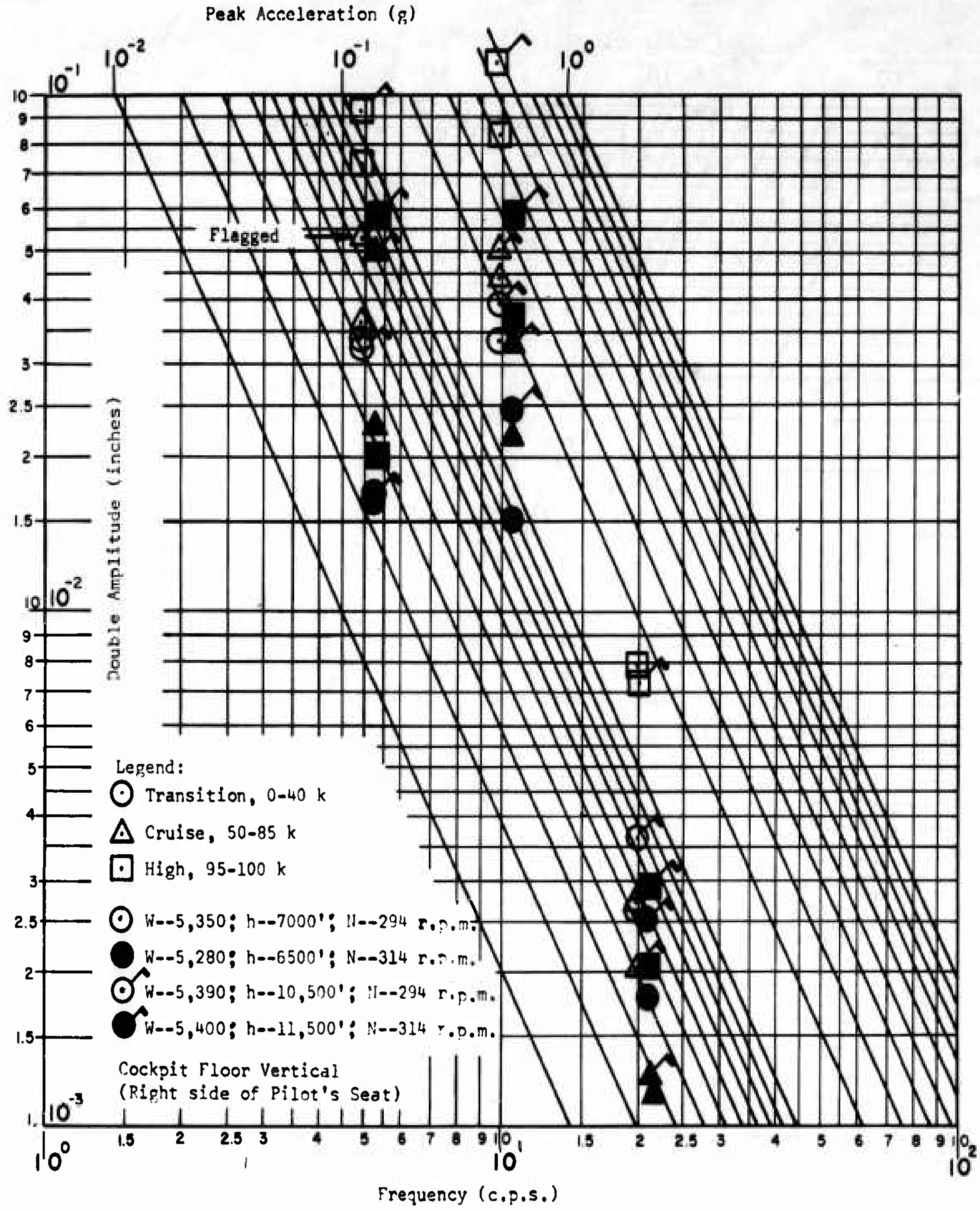


Figure 12a. Vibration Data for the Model XH-40 Bell.

-40-

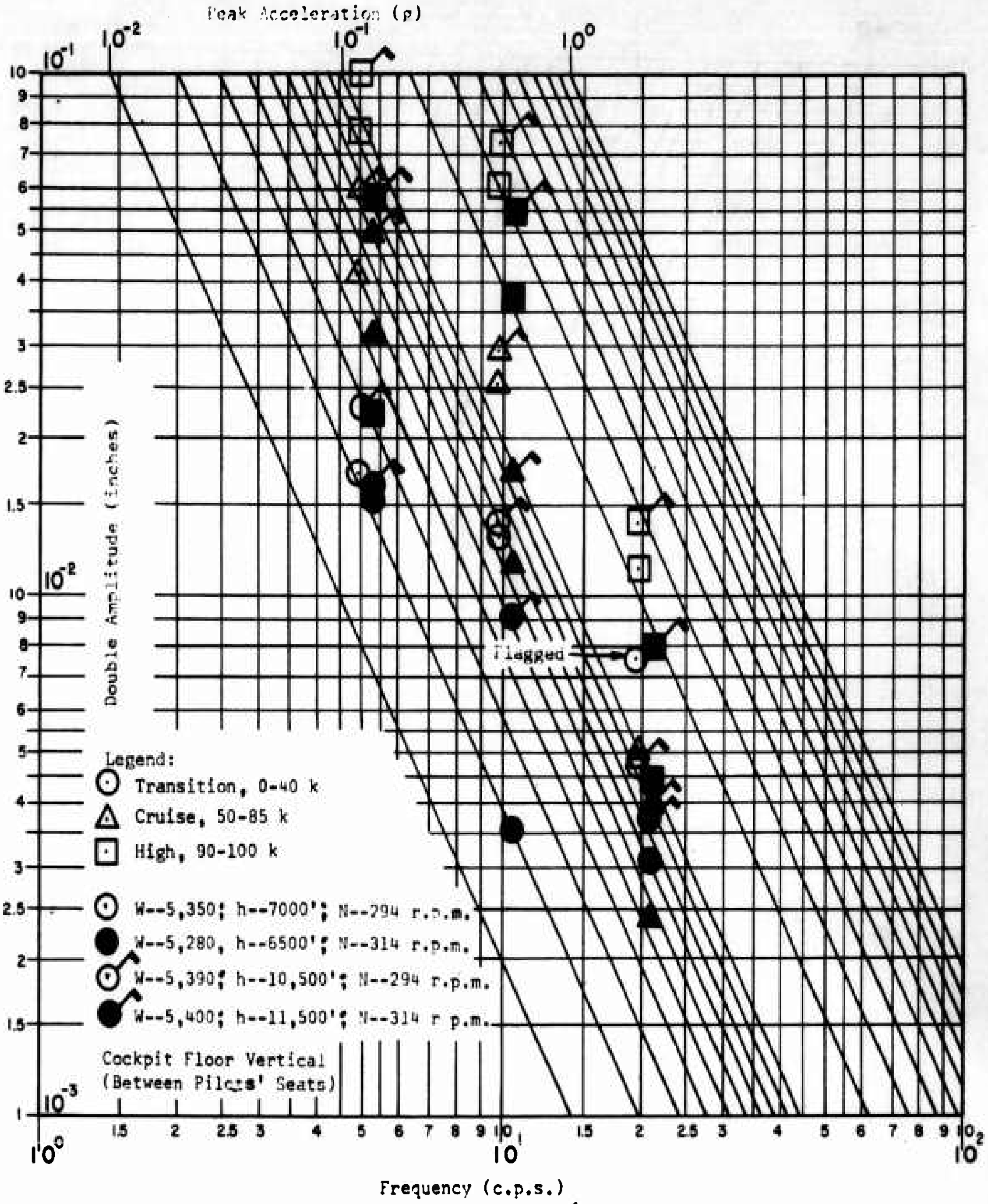


Figure 12b. Vibration Data for the Model XH-40 Bell.

-41-

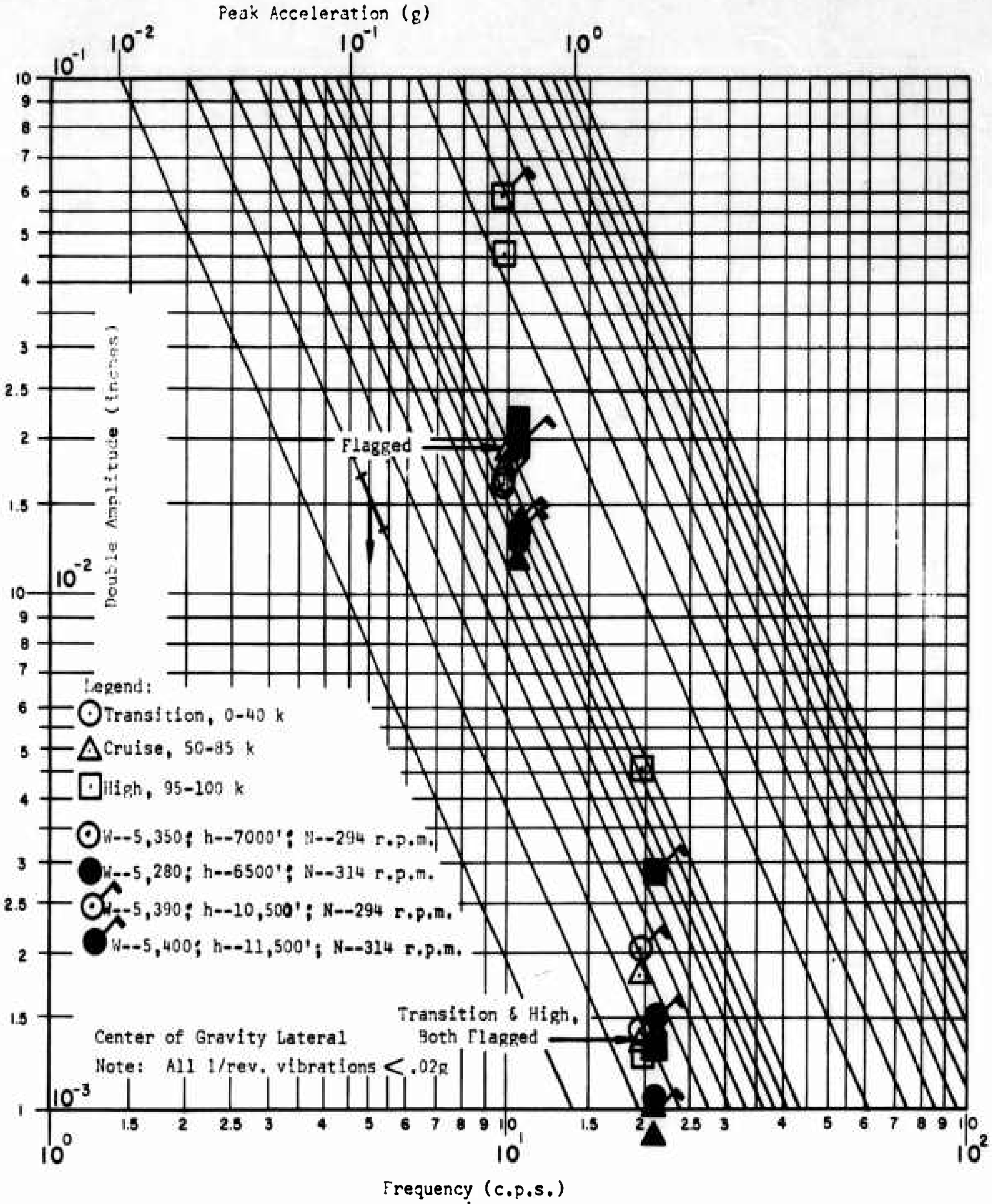


Figure 12c. Vibration Data for the Model XH-40 Bell.

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APPENDIX

FLIGHT TEST PROGRAM.

Objectives: 1. To establish the reliability and operational characteristics of the helicopter vibration indication system for the H-21 helicopter.

2. To establish a firm specification for the vibration alarm limits.

Statement of Procedure: Five helicopter vibration indication units have been fabricated. It is suggested that four units be employed in this test program, with one unit placed in reserve for possible employment in temperature and environment tests.

The four units to be employed in the flight test program may be deployed by installing three units on helicopters and keeping one unit on standby for replacement of the active units during the calibration period. It is suggested that the active units be recalibrated at 10-hour periods initially until some experience with the reliability of the unit has been developed. It should be possible to minimize the ground maintenance time for the helicopter by rotating four units through three helicopters as outlined above.

It would be desirable if the flight plan outlined below were followed for each flight and data recorded for each condition specified, and it would also be desirable if the takeoff gross weight were varied over the full range from minimum to maximum weight. Several tests should also be conducted for external loads.

Flight Plan:

1. Hovering flight.
   - a. Engine speed 2500 r.p.m., in-ground effect.
   - b. Engine speed 2400 r.p.m., in-ground effect.
   - c. Engine speed 2700 r.p.m., in-ground effect.
   - d. Repeat a thru c, out-of-ground effect.
2. Takeoff, standard takeoff, r.p.m. as required.
3. Powered climb, maximum rate of climb to cruise altitude, r.p.m. as required.
4. Level flight at cruise altitude and r.p.m.
   - a. Velocity, 40 knots.
   - b. Velocity, 60 knots.
   - c. Velocity, 80 knots.
   - d. Velocity, maximum.
5. Cruise flight.
   - a. Cruise speed, 2500 r.p.m.
   - b. Cruise speed, 2400 r.p.m.
   - c. Cruise speed, 2700 r.p.m.

6. Banked 360° turn, speed and r.p.m. as required.

   a. Long, smooth turn.
   b. Sharp, banked turn.

7. Power descent, r.p.m. as required.

8. Powered landing, standard approach, r.p.m. as required.

9. Autorotation descent, speed for minimum rate of descent, r.p.m. as required.

Estimated Time:
1. Installation, 4 hours.
2. Replacement of unit, 2 hours.
3. Removal of unit and reconditioning of helicopter, 4 hours.

APPENDIX III

CALIBRATION CURVES

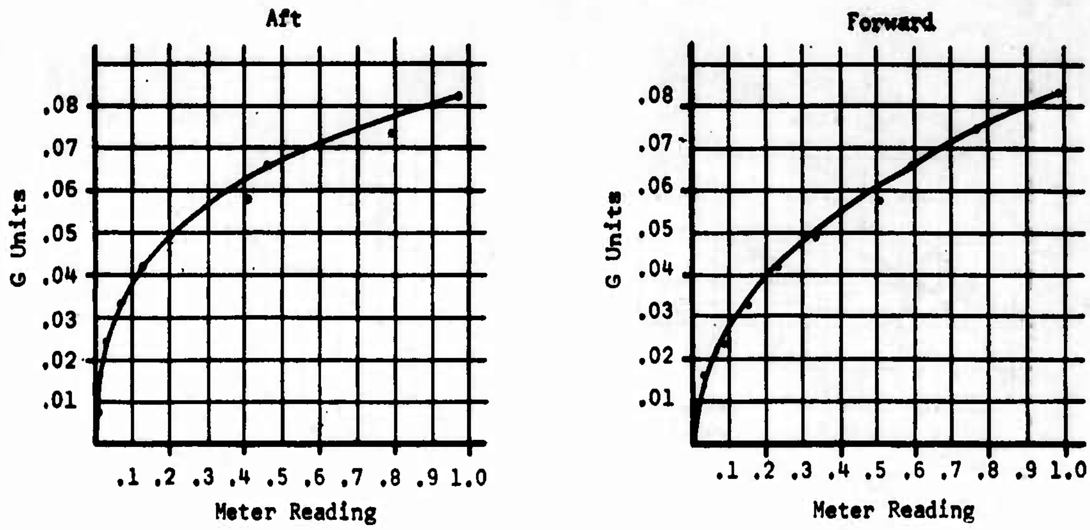


Figure 3. Calibration Curve for 1/rev. Channel, Unit 97V1001.

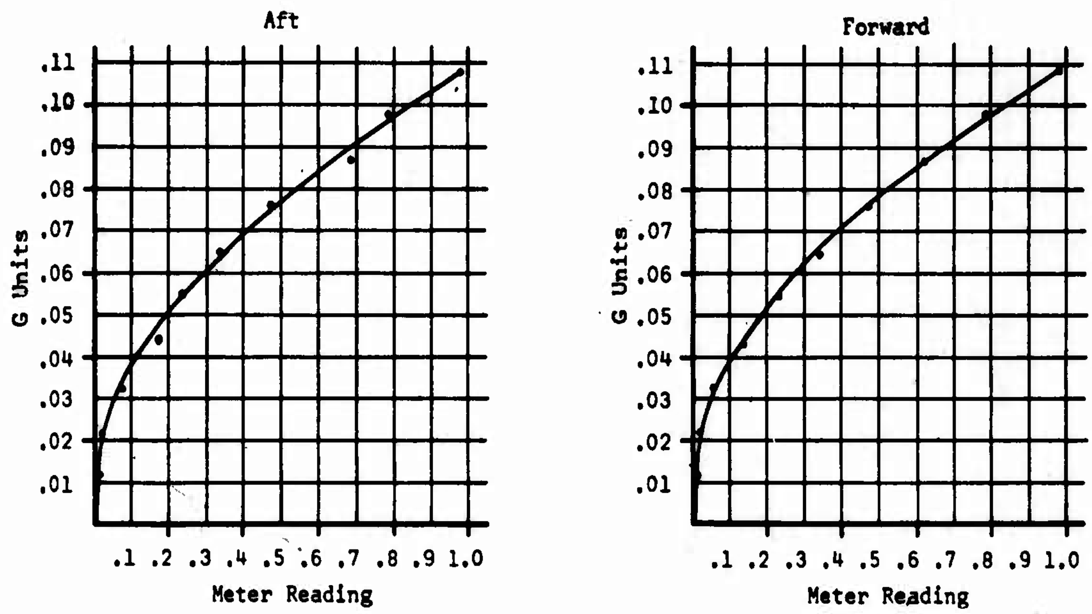


Figure 4. Calibration Curve for 2/rev. Channel, Unit 97V1001.

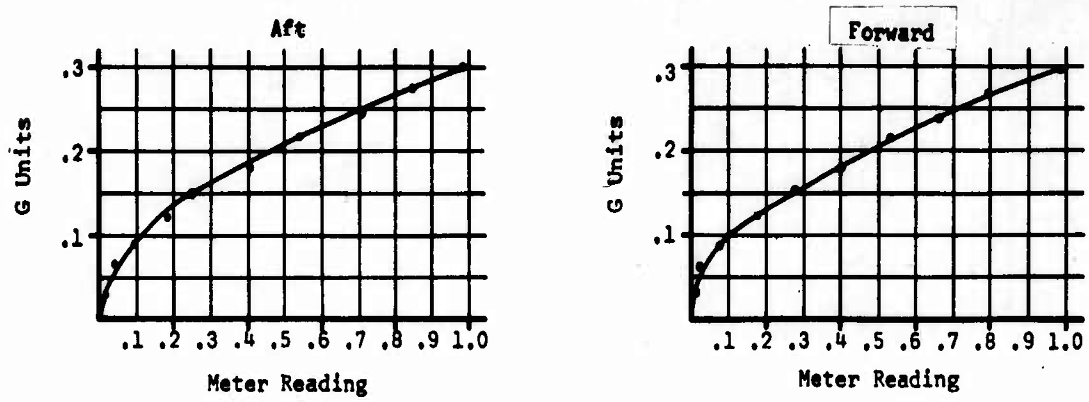


Figure 5. Calibration Curve for 3/rev. Channel, Unit 97V1001.

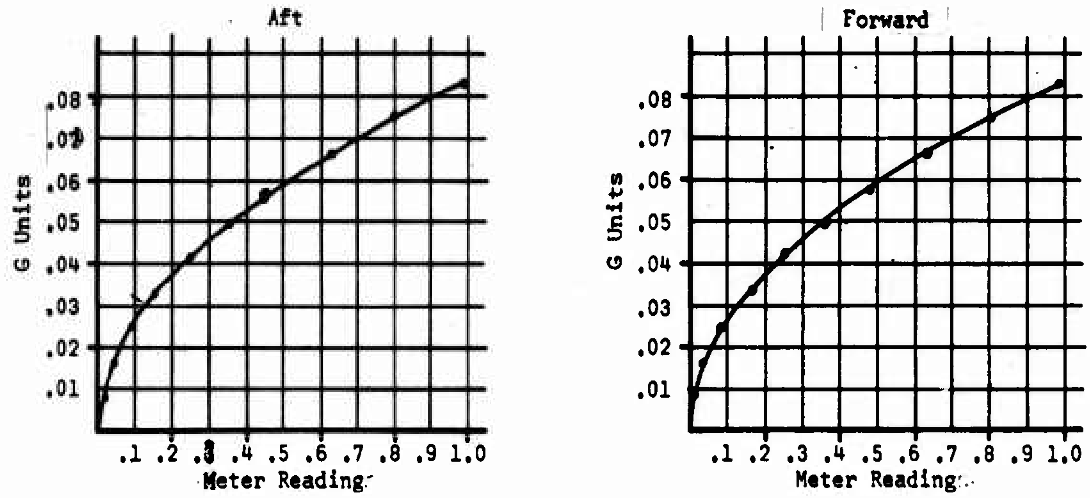


Figure 6. Calibration Curve for 1/rev. Channel, Unit 97V1002.

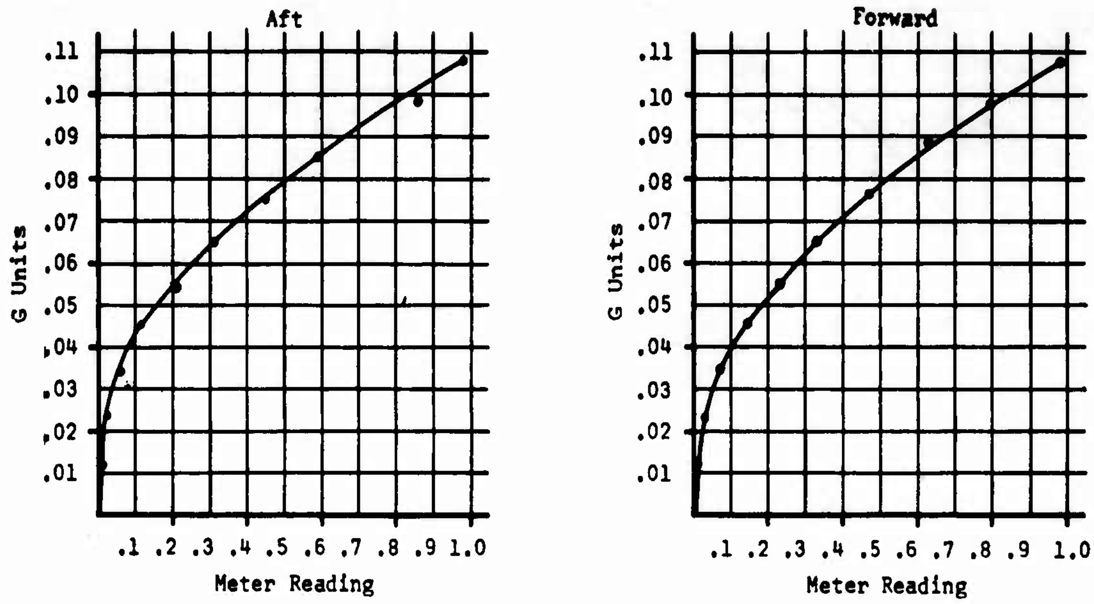


Figure 7. Calibration Curve for 2/rev. Channel, Unit 97V1002.

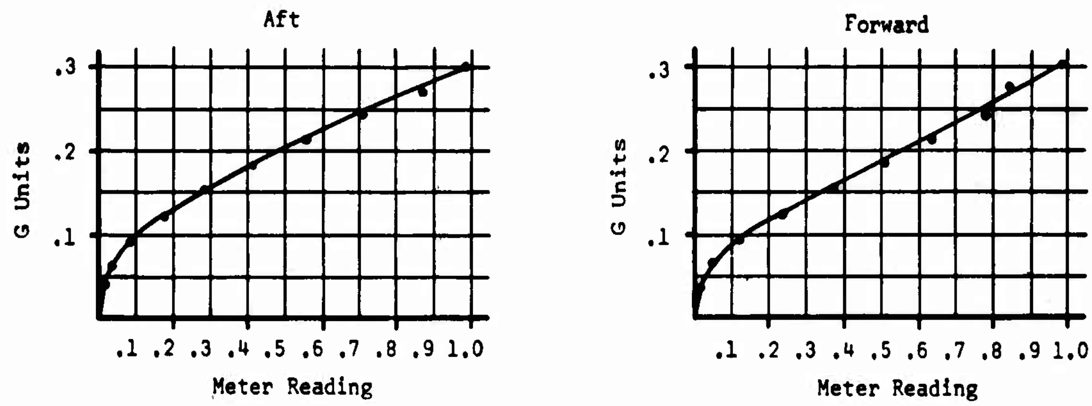


Figure 8. Calibration Curve for 3/rev. Channel, Unit 97V1002.

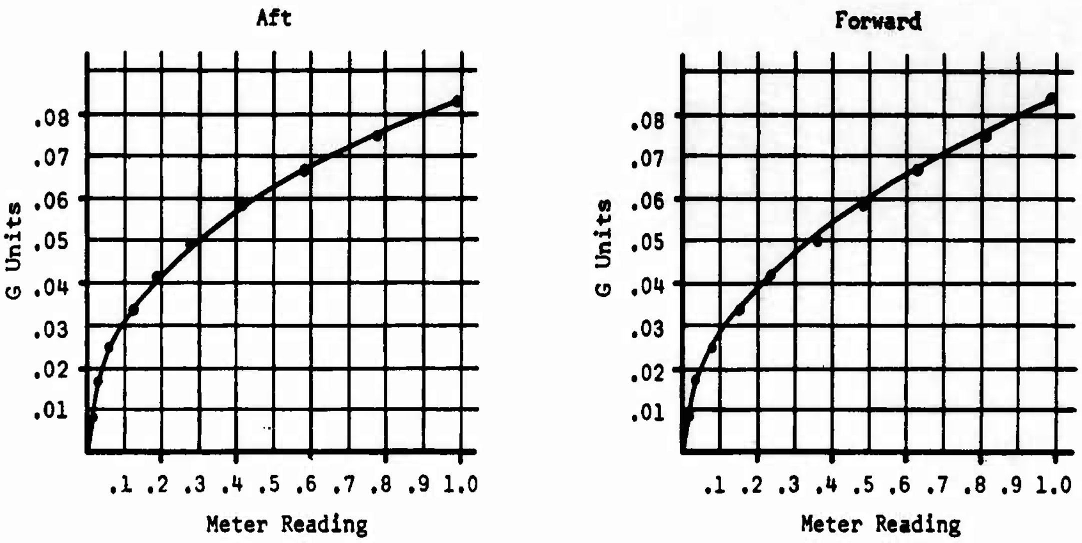


Figure 9. Calibration Curve for 1/rev. Channel, Unit 97V1003.

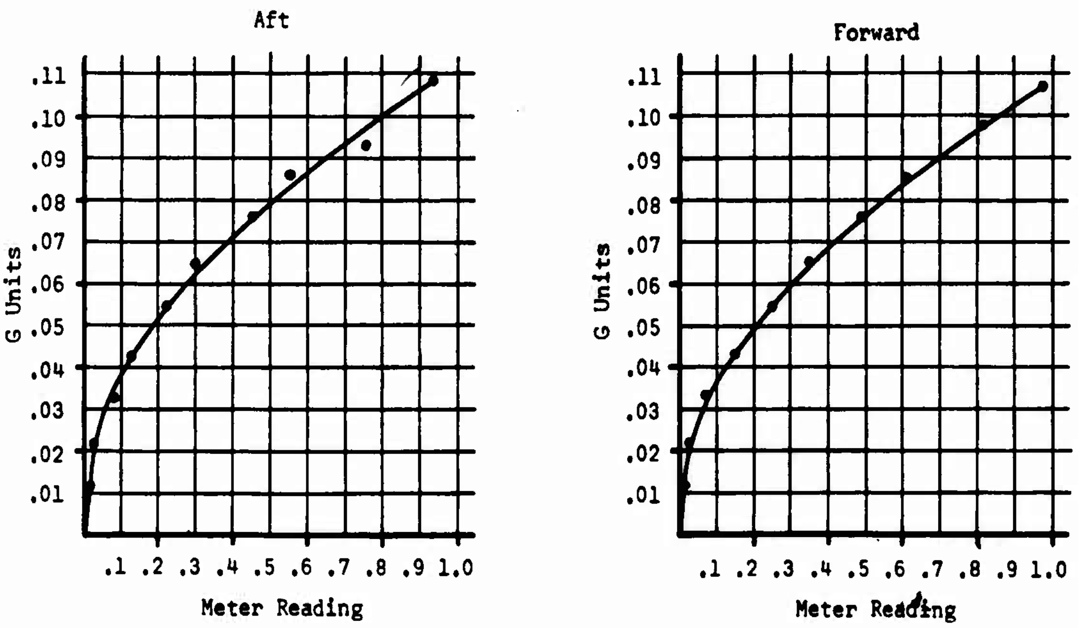


Figure 10. Calibration Curve for 2/rev. Channel, Unit 97V1003.

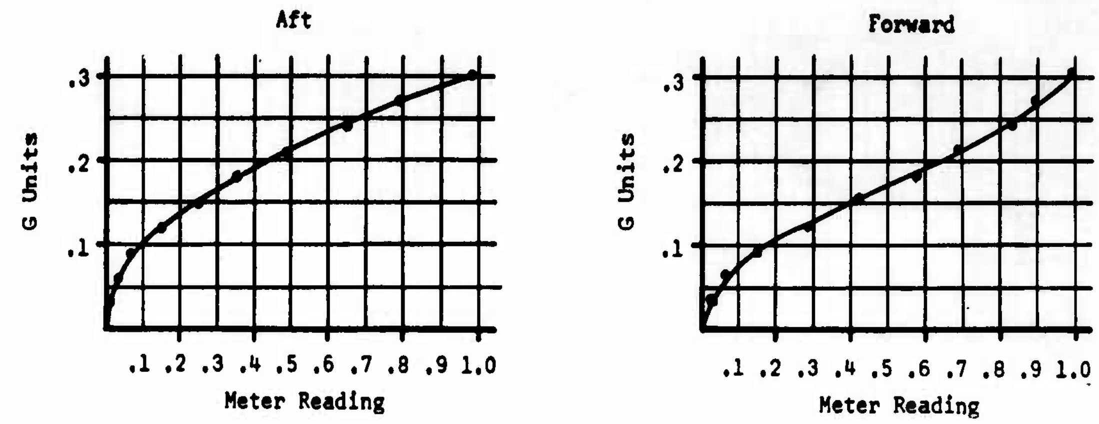


Figure 11. Calibration Curve for 3/rev. Channel, Unit 97V1003.

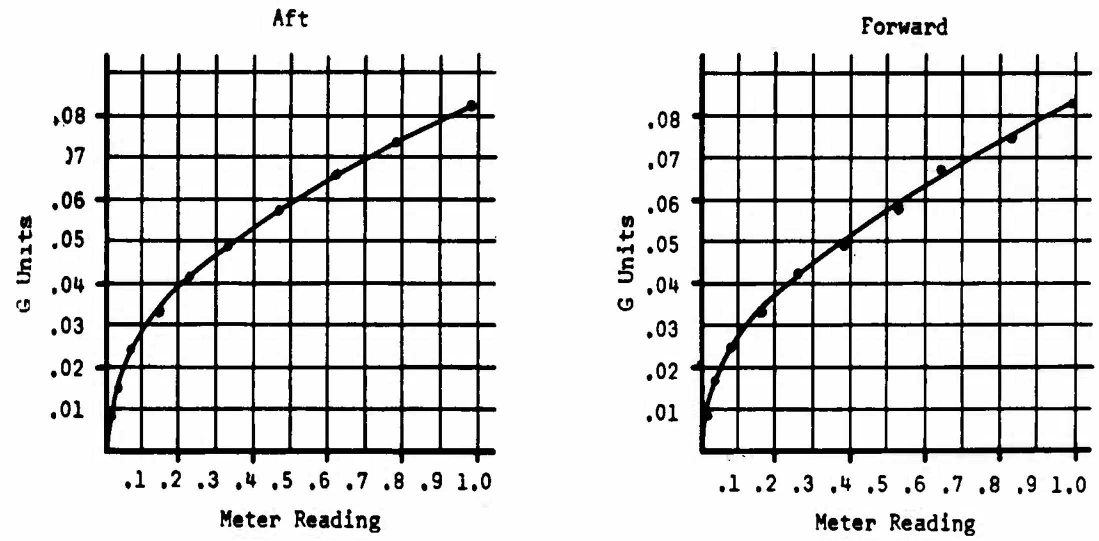


Figure 12. Calibration Curve for 1/rev. Channel, Unit 97V1004.

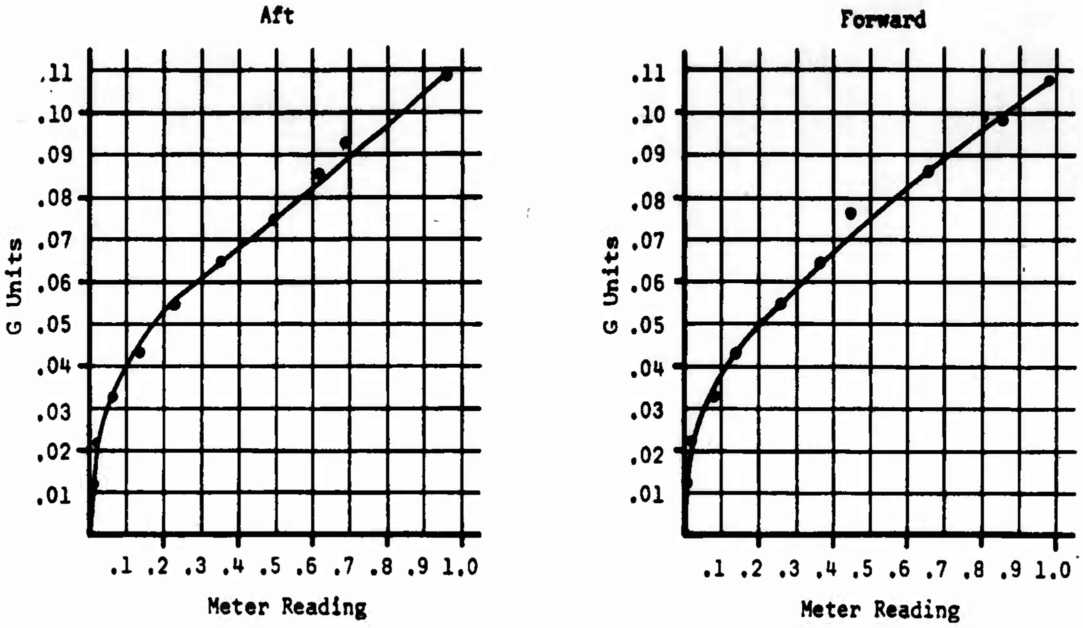


Figure 13. Calibration Curve for 2/rev. Channel, Unit 97V1004.

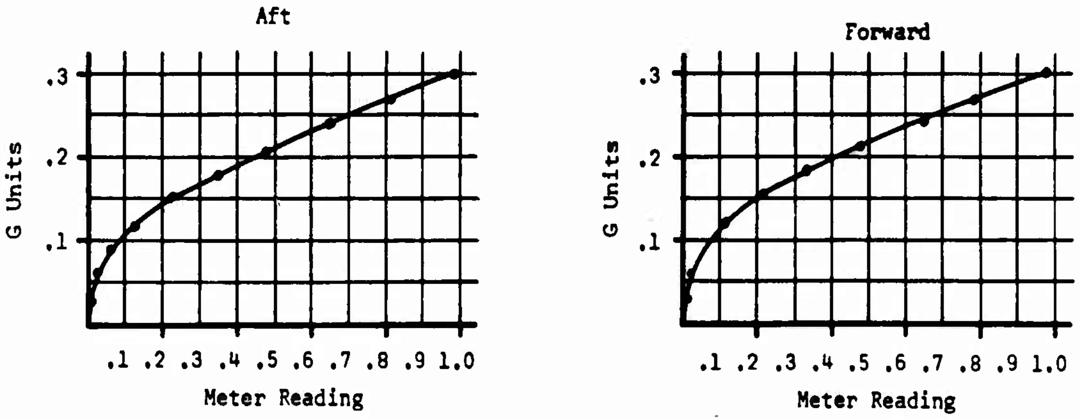


Figure 14. Calibration Curve for 3/rev. Channel, Unit 97V1004.

APPENDIX IV

INSTALLATION PROCEDURES AND PHOTOGRAPHS OF VIBRATION INDICATOR INSTALLATION

1. Shake Table. Figure 15 shows a picture of the shake table used for calibration.

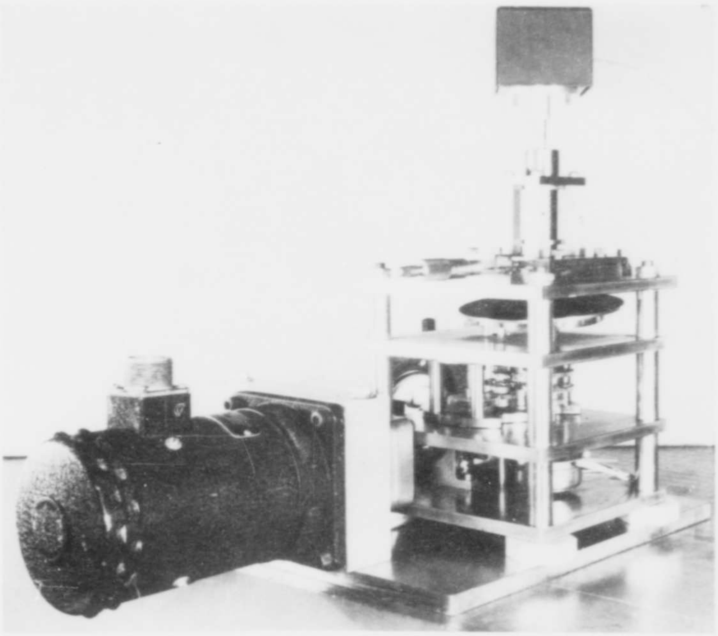


Figure 15. Calibration Shake Table.

2. Main Analyzer Chassis. It is recommended that the main analyzer chassis be mounted on a 1/2-inch plywood board. The board should extend approximately 2 to 3 inches beyond the chassis mounts. Two screw eyelets should be installed at each end of the board. The chassis, mounted on the board, may then be tied directly to the cargo deck by means of the cargo tiedowns. The chassis should be positioned well forward in the cargo compartment, to the left and immediately aft of the pilot's compartment, as shown in Figure 16 on page 76.

3. Reference Signal Generator. The reference signal generator is mounted on the rotor tachometer generator pad located on the central transmission, as shown in Figure 17.

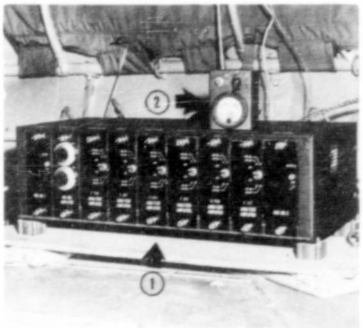


Figure 16. Mounting of Analyzer Cabinet (Arrow 1) and Pilot Display (Arrow 2).

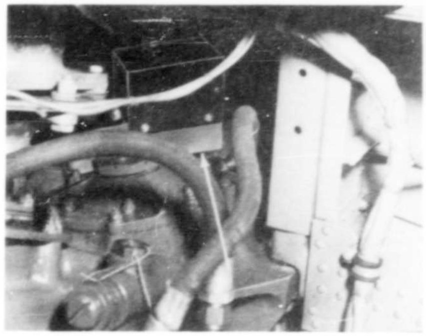


Figure 17. Mounting of Reference Signal Generator. (Indicated by arrow.)

The procedure for installing the reference signal generator is as follows:

a. Remove the rotor tachometer generator.

b. Remove the mounting studs and replace with AN126126 studs.

c. Mount the reference signal generator on studs with the square input shaft toward the central transmission; place thumb on the shaft output (square female), and turn to align the input shaft as the reference signal generator is installed.

d. Mount the rotor tachometer generator on the studs extending from the reference signal generator.

e. Bolt the rotor tachometer generator and reference signal generator in place with elastic stop nuts (1/4-28); place a 1/16-inch aluminum washer under each nut.

4. Vibration Pickups. The pickups are mounted to any main structure where it would be either desirable or advantageous to establish the vibration levels (see Figures 18 and 19 for one set of positions).

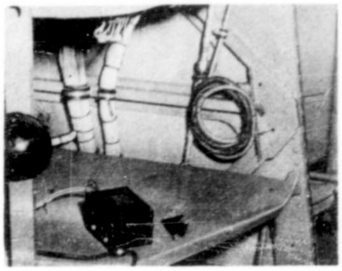


Figure 18. Mounting of Forward Pickup. (Arrow indicates pickup.)

Figure 19. Mounting of Aft Pickup. (Arrow indicates pickup.)

The general procedure is as follows:

a. Remove the dust cover from the pickup assembly.

b. Loosen bolts holding the accelerometer.

c. Select the location for the pickup to be mounted; be sure that the final position of the pickups will be parallel to the horizontal plane and that there is sufficient clearance for both the pickup and the attached cable.

d. Drill two .191-inch holes, 1.5 inches on center, and mount pickups with number 10 bolts.

e. Use elastic stop nuts or equivalent.

5. <u>Power Cable.</u> Power for the analyzer chassis is taken from a 5-ampere circuit breaker normally used for litter lights. The connection is made inside the d.-c. distribution box.

6. <u>Other Cables.</u> Attachments of convenience to the aircraft structure should be made approximately every 2 to 3 feet of cable length.

APPENDIX V

FLIGHT DATA

This Appendix presents the results of the flight tests on the helicopter vibration indicator. Unit 97V1001 was tested on flights I (14 July 1960) and II (15 July 1960); Unit 97V1002 was tested on flights III (19 September 1960) and IV (21 September 1960); Unit 97V1004 was tested on flight V (26 September 1960), and the contractor's data are presented as flight VI (11-18 September 1959).

A flight test plan recommended by the contractor was followed on all flights. This plan is as follows:

1. Hover Flight.
   a. Engine speed 2500 r.p.m., in-ground effects.
   b. Engine speed 2700 r.p.m., in-ground effects.
   c. Down wind, r.p.m. as required, in-ground effects.
   d. Cross wind, r.p.m. as required, in-ground effects.
   e. Engine speed 2500 r.p.m., out-of-ground effects.
   f. Engine speed 2700 r.p.m., out-of-ground effects.
   h. Down wind, r.p.m. as required, out-of-ground effects.
   i. Cross wind, r.p.m. as required, out-of-ground effects.

2. Normal takeoff, r.p.m. as required.

3. Powered climb, maximum rate of climb to cruise altitude, r.p.m. as required.

4. Level flight at cruise altitude and cruise r.p.m., with velocity as noted.
   a. 50 knots.
   b. 60 knots.
   c. 80 knots.
   d. Maximum.

5. Cruise flight.
   a. Speed, 2400 r.p.m.
   b. Speed, 2500 r.p.m.

6. Banked 360° turns, speed and r.p.m. as required.
   a. Long, smooth turn.
   b. Sharp, banked turn.

7. Normal descent, r.p.m. as required (29" Hg manifold pressure).

8. Powered landing, standard approach.

9. Powered landing, steep approach.

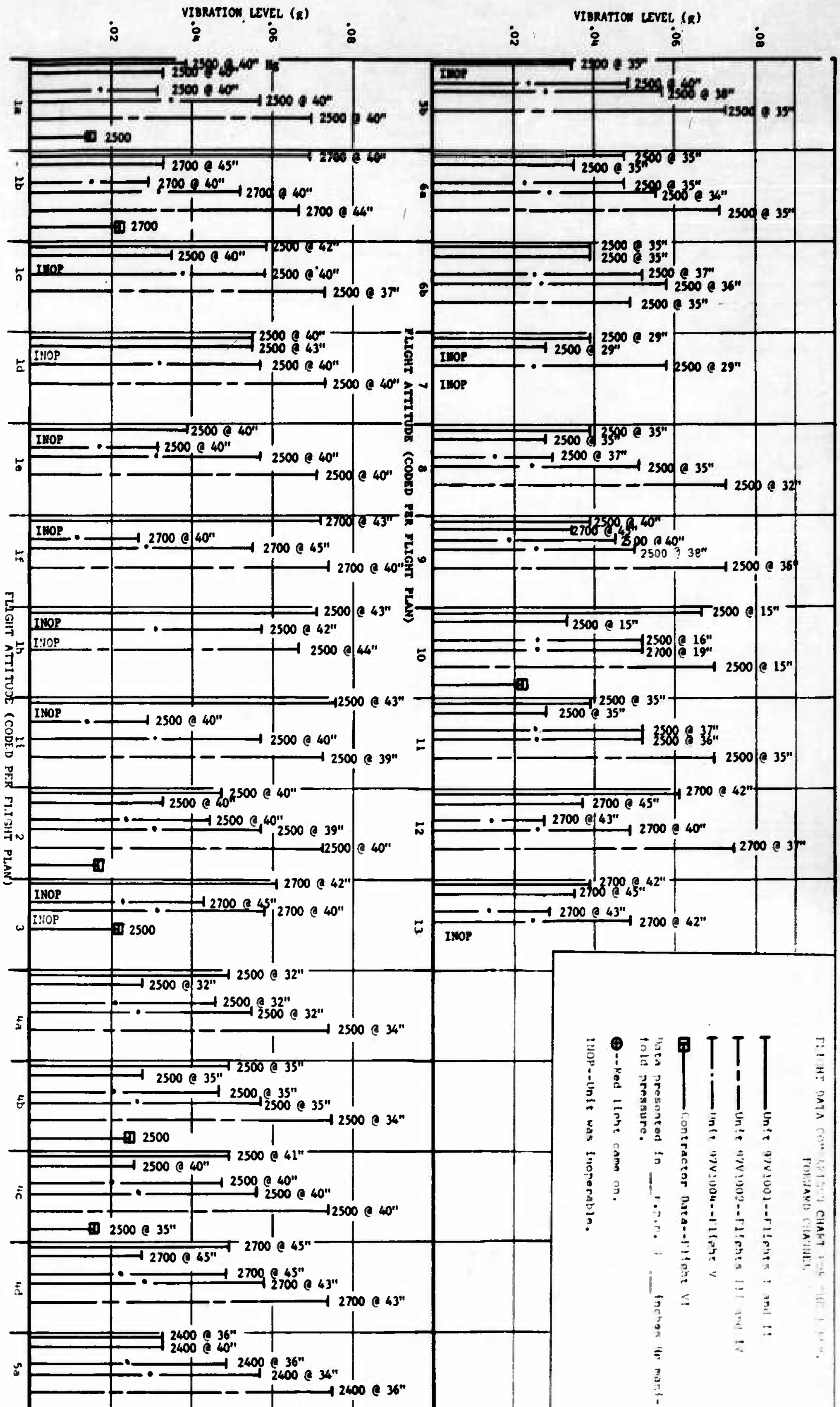
10. Autorotation descent, speed for minimum rate of descent, r.p.m. as required.

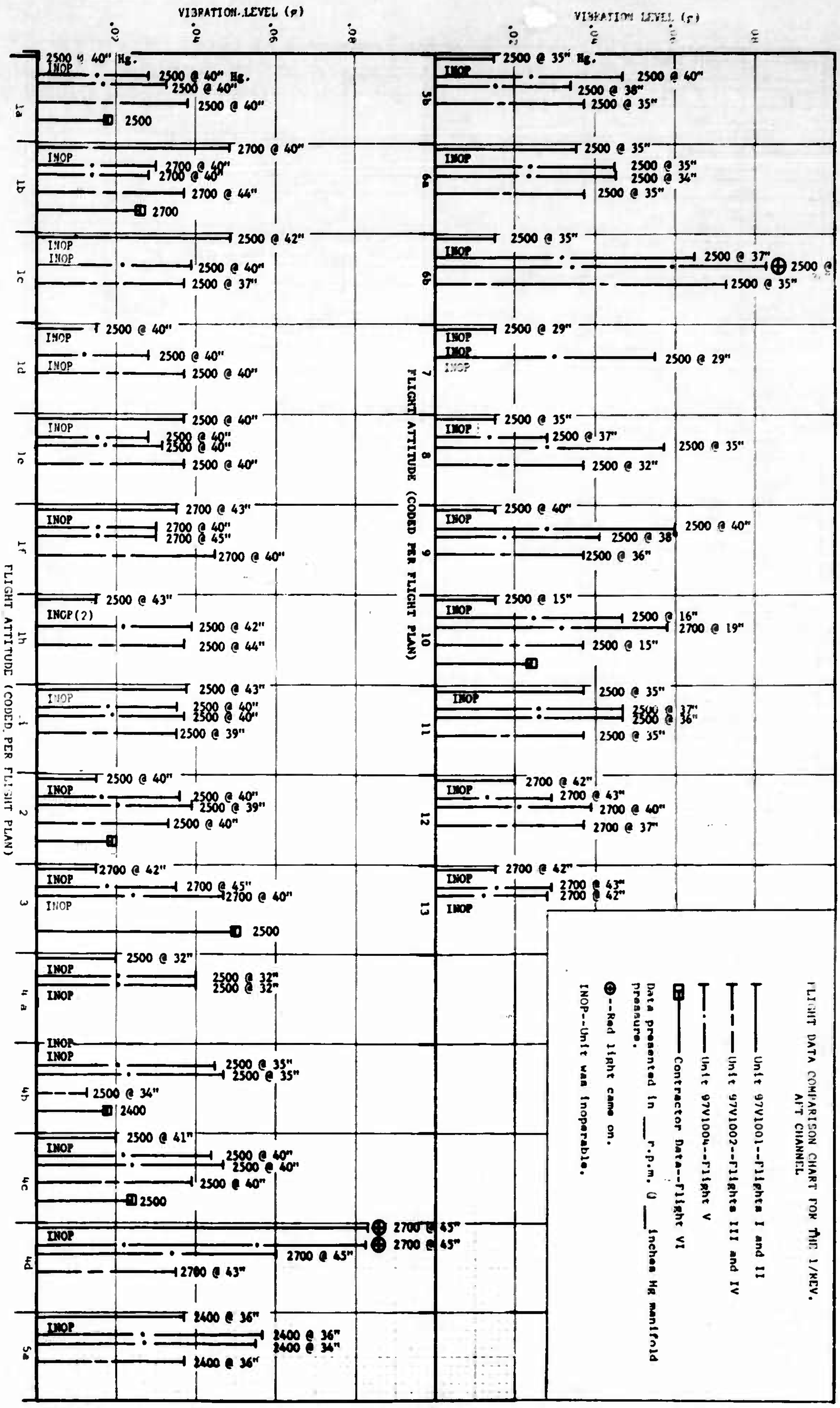
11. Power recovery from autorotation descent.

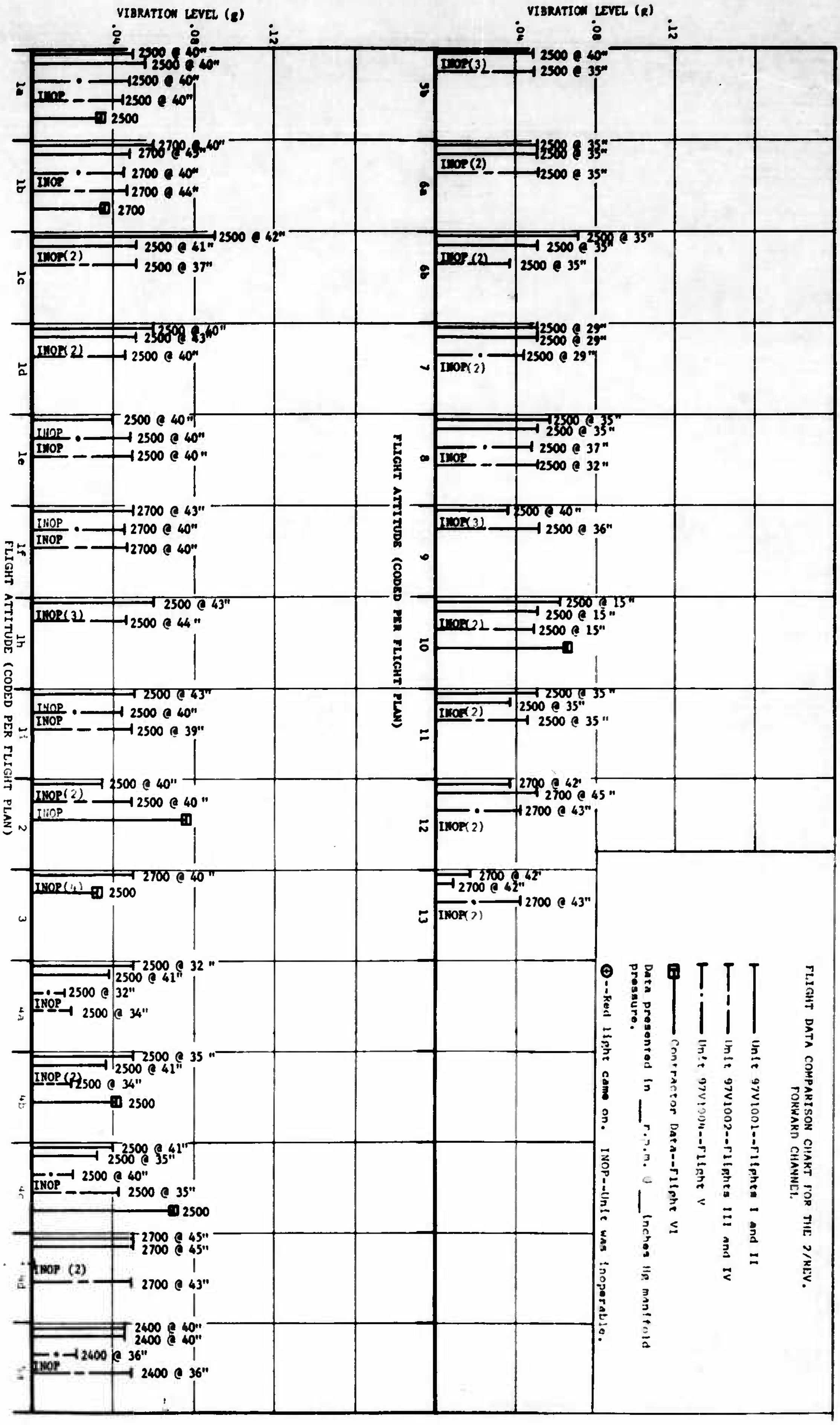
12. Maximum performance takeoff, r.p.m. as required.

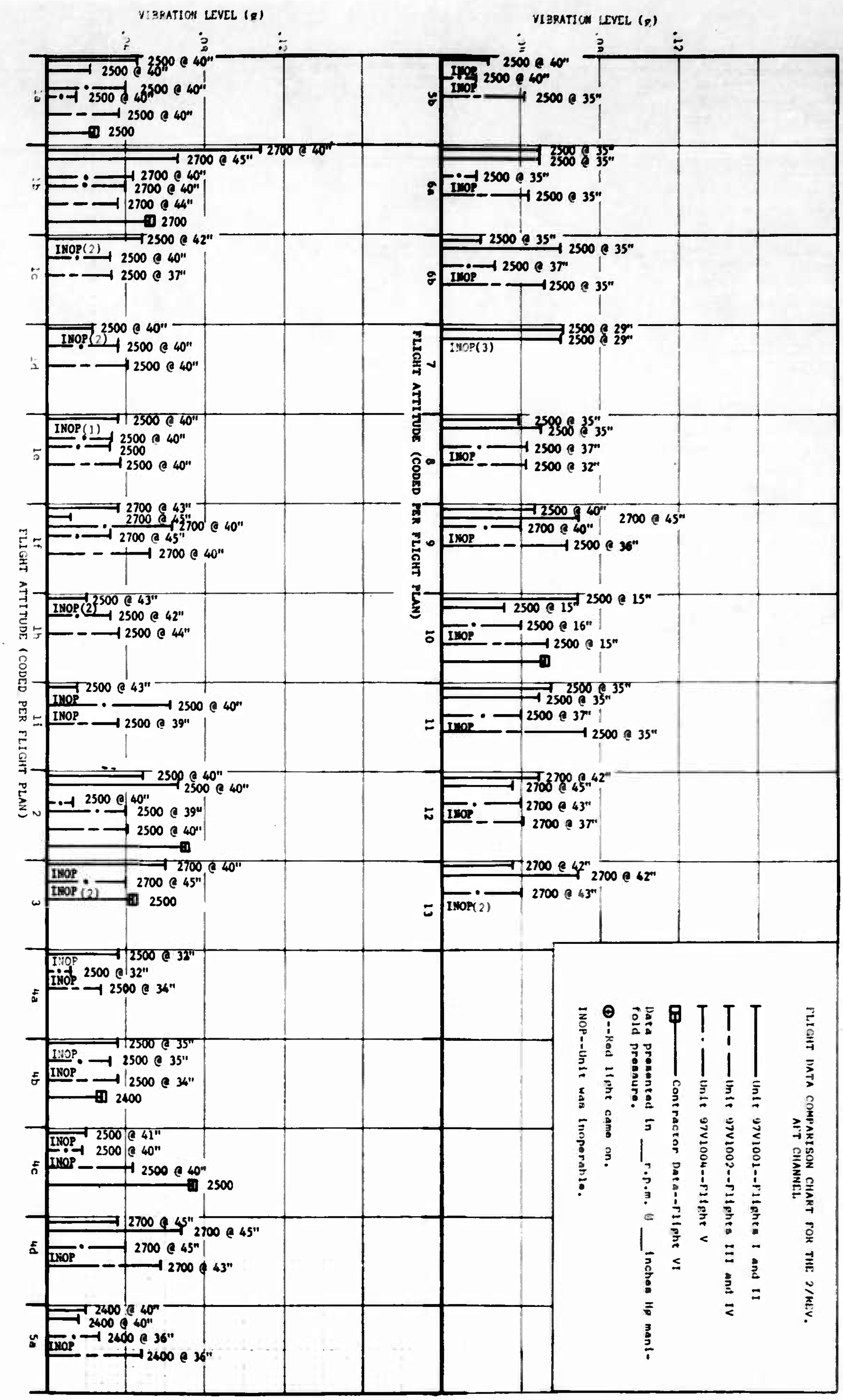
13. Confined area takeoff, r.p.m. as required.

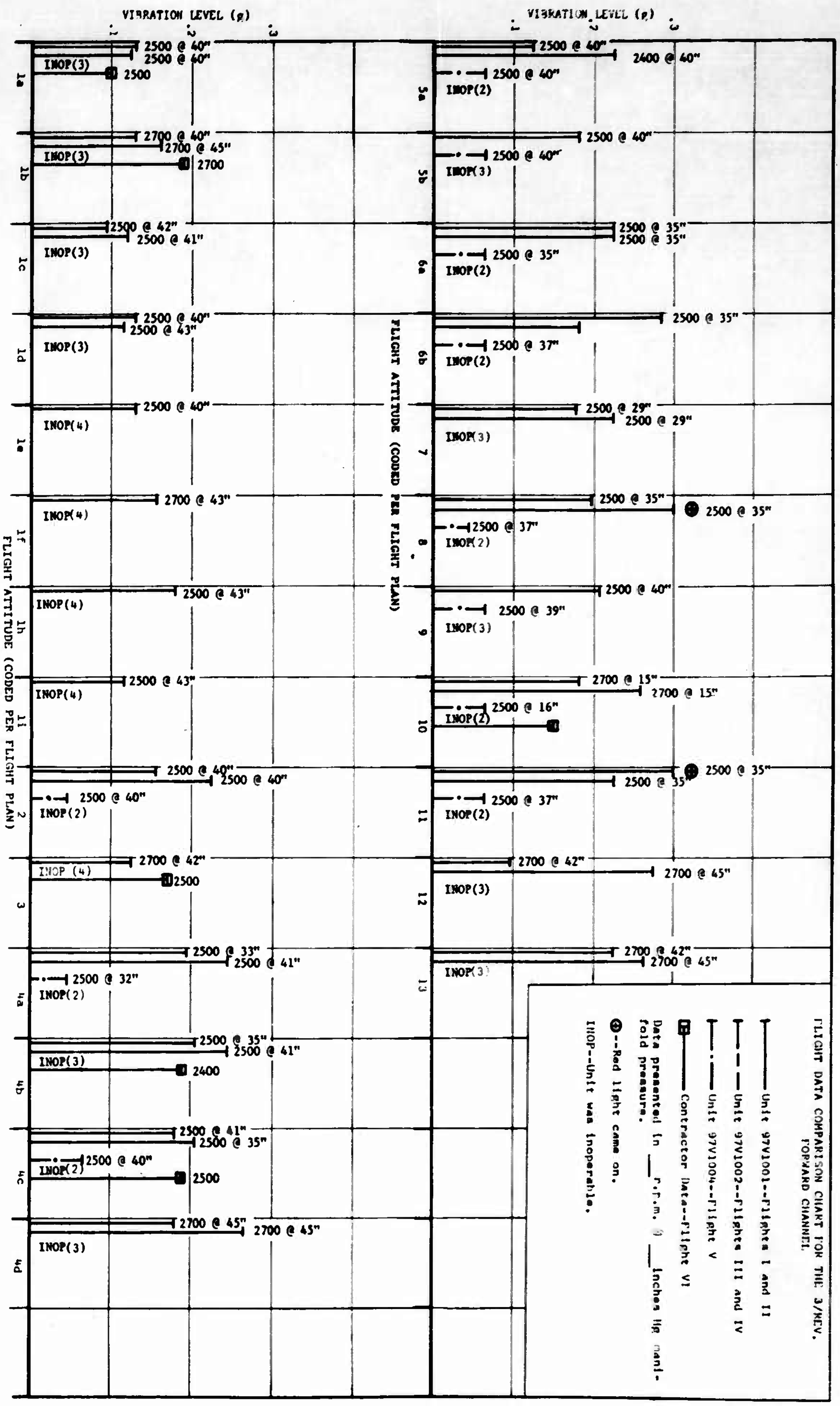
The data obtained from these tests are presented in the Flight Data Comparison Charts. The flight conditions under which each test was made are identified by numerals and letters which refer to the Flight Test Plan. INOP indicates that a channel was inoperable on a particular flight, while a number following in parentheses indicates the number of channels that were inoperable. Since the contractor's data were not always available, this space was sometimes left blank.


VIBRATION LEVEL (g)
FLIGHT ATTITUDE (CODED PER FLIGHT PLAN)
FORWARD CHANNEL
Unit 97V1001--Flights I and II
Unit 97V1002--Flights III and IV
Unit 97V1004--Flight V
Contractor Data--Flight VI
Data presented in ___ R.P.M. @ ___ inches Hg manifold pressure.
--Red light came on.
INOP--Unit was inoperable.

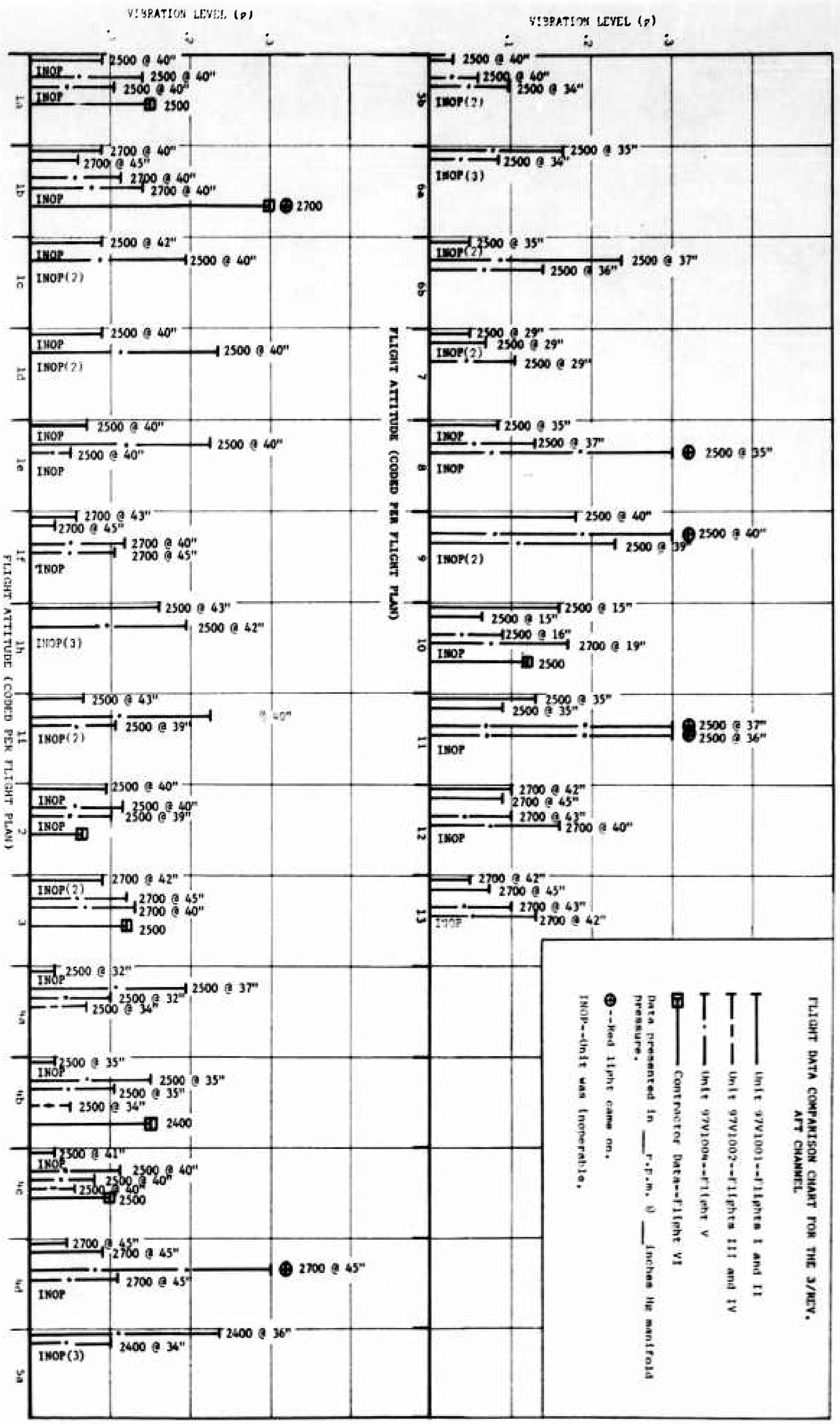

FLIGHT DATA COMPARISON CHART FOR THE 1/REV. AFT CHANNEL
Unit 97V1001--Flights I and II
Unit 97V1002--Flights III and IV
Unit 97V1004--Flight V
Contractor Data--Flight VI
Data presented in ___ r.p.m. @ ___ inches Hg manifold pressure.
⊕--Red light came on.
INOP--Unit was inoperable.
VIBRATION LEVEL (g)
FLIGHT ATTITUDE (CODED PER FLIGHT PLAN)


FLIGHT DATA COMPARISON CHART FOR THE 2/REV. FORWARD CHANNEL.
VIBRATION LEVEL (g)
.04
.08
.12
FLIGHT ATTITUDE (CODED PER FLIGHT PLAN)
Unit 97V1001--Flights I and II
Unit 97V1002--Flights III and IV
Unit 97V1004--Flight V
Contractor Data--Flight VI
Data presented in ___ r.p.m. @ ___ inches Hg manifold pressure.
--Red light came on. INOP--Unit was inoperable.


FLIGHT DATA COMPARISON CHART FOR THE 2/REV. A/T CHANNEL
VIBRATION LEVEL (g)
FLIGHT ATTITUDE (CODED PER FLIGHT PLAN)
Unit 97V1001--Flights I and II
Unit 97V1002--Flights III and IV
Unit 97V1004--Flight V
Contractor Data--Flight VI
Data presented in ___ r.p.m. @ ___ inches Hg manifold pressure.
--Red light came on.
INOP--Unit was inoperable.



VIBRATION LEVEL (g)
.1
.2
.3
FLIGHT ATTITUDE (CODED PER FLIGHT PLAN)
1a
2500 @ 40"
2500 @ 40"
INOP(3)
2500
1b
2700 @ 40"
2700 @ 45"
INOP(3)
2700
1c
2500 @ 42"
2500 @ 41"
INOP(3)
1d
2500 @ 40"
2500 @ 43"
INOP(3)
1e
2500 @ 40"
INOP(4)
1f
2700 @ 43"
INOP(4)
1h
2500 @ 43"
INOP(4)
1i
2500 @ 43"
INOP(4)
2
2500 @ 40"
2500 @ 40"
2500 @ 40"
INOP(2)
3
2700 @ 42"
INOP (4)
2500
4a
2500 @ 33"
2500 @ 41"
2500 @ 32"
INOP(2)
4b
2500 @ 35"
2500 @ 41"
INOP(3)
2400
4c
2500 @ 41"
2500 @ 35"
2500 @ 40"
INOP(2)
2500
4d
2700 @ 45"
2700 @ 45"
INOP(3)
5a
2500 @ 40"
2400 @ 40"
2500 @ 40"
INOP(2)
5b
2500 @ 40"
2500 @ 40"
INOP(3)
6a
2500 @ 35"
2500 @ 35"
2500 @ 35"
INOP(2)
6b
2500 @ 35"
2500 @ 37"
INOP(2)
7
2500 @ 29"
2500 @ 29"
INOP(3)
8
2500 @ 35"
2500 @ 35"
2500 @ 37"
INOP(2)
9
2500 @ 40"
2500 @ 39"
INOP(3)
10
2700 @ 15"
2700 @ 15"
2500 @ 16"
INOP(2)
11
2500 @ 35"
2500 @ 35"
2500 @ 37"
INOP(2)
12
2700 @ 42"
2700 @ 45"
INOP(3)
13
2700 @ 42"
2700 @ 45"
INOP(3)
FLIGHT DATA COMPARISON CHART FOR THE 3/REV. FORWARD CHANNEL.
Unit 97V1001--Flights I and II
Unit 97V1002--Flights III and IV
Unit 97V1004--Flight V
Contractor Data--Flight VI
Data presented in ___ r.p.m. @ ___ inches Hg manifold pressure.
--Red light came on.
INOP--Unit was inoperable.


VIBRATION LEVEL (g)
FLIGHT ATTITUDE (CODED PER FLIGHT PLAN)
FLIGHT DATA COMPARISON CHART FOR THE 3/REV, AFT CHANNEL
Unit 97V1001--Flights I and II
Unit 97V1002--Flights III and IV
Unit 97V1004--Flight V
Contractor Data--Flight VI
Data presented in ___r.p.m. @ ___inches Hg manifold pressure.
--Red light came on.
INOP--Unit was inoperable.

APPENDIX VI

MEMORANDUM REPORT
CALIBRATION TEST - VIBRATION ANALYZER
MR-97-001

INTRODUCTION

From March 14 through March 16, 1960, a calibration test of the five completed units indicated that four of the units had drifted excessively off the initial calibration.[1] On previous tests conducted on unit number one for a comparable period of time, the system had indicated substantial calibration reliability. Calibration tests conducted on unit number one subsequent to the last flight test of this unit indicated that five of the channels were within one-half of a major meter division (.05), or approximately 3 to 5 percent of maximum g error. The sixth channel of this unit was high by about three major meter divisions (.3), or very nearly 25 percent of maximum g error. At the time of this test, it was suspected that this channel had been inadvertently adjusted during flight test.

The alarm system, and in particular the thermal delay relays, also exhibited erratic characteristics.[2] The cause of this erratic behavior was initially attributed to an unknown characteristic of the relays; however, upon closer and more comprehensive review of the calibration, it was observed that those channels whose thermal delay relay's behavior was most erratic were also those whose calibration had drifted below the original settings. Since the high and low alarms were adjusted to a given signal level (voltage) from the analyzer, any change in the calibration level would result in an apparent erratic behavior of the alarm system. Presently, it is believed that the basic problem is an excessive drift in calibration.

With this thought in mind, the contractor embarked upon a calibration test conducted daily over a 6-week period in order to establish the drift in

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[1] Paragraph g, TCREC-ADS 9R38-01-017-41, letter of 25 March 1960.

[2] Ibid., paragraph e.

calibration. Several components of the design were suggested as potential sources of calibration drift. These are as follows:

a. Band-pass filters and oscillator controls - variations in amplitude and/or frequency.

b. Resolvers - variation in output signal.

c. Vibration pickup - variation in output signal.

d. Transistors - variation in gain characteristics.

e. Alarm relays - loading effect of alarms on the calibrated output.

f. Shake table - mechanical variation in either the frequency or amplitude or in both.

It was considered entirely possible that either shelf or active (operational life) aging and/or ambient temperature variation in combination with one or more of the above-mentioned items could be the fundamental cause of calibration drift.

TEST PROCEDURES AND RESULTS

Unit number five was employed in the test program. This unit was calibrated on March 22, 1960, and no further adjustment was made in the calibration adjustment. On March 23, three readings were recorded, and it was observed that five of the six channels were down from the preceding day's run. As noted on Table 1, the order in which the channels were tested was alternated, starting with the forward channel and then the aft channel (F and A) for test number 1 and reversing (A and F) for test 2. The sequence in which the harmonics were tested for any one pickup was varied randomly, but generally the first pickup tested was recorded in the sequence 3, 2, and 1, and the second pickup in reverse order 1, 2, and 3. At this time the possibility of rejecting the first day's run and taking an average of tests 2, 3, and 4 (see Table 4 on page 93) was considered. During this day's run the unit was left on continuously.

Eight tests were run from March 24 to March 26, with power on the unit maintained throughout this period. It was observed that the voltage output for oscillator number one was down initially (test 5). No pronounced effect was observed on the forward channels; however, two of the aft channels were down and one up initially. These channels appeared to steady (tests 6 and 7); however, with the exception of 3F, all channels tended to lower average readings (tests 5 through 12).

TABLE 1
CALIBRATION TEST RESULTS

Test No.	Osc. 1 Voltage (rms)	Channel 3F		Channel 2F		Channel 1F		Channel 3A		Channel 2A		Channel 1A		Conditions
	m. / f. / g	.16 / 13.5 / .300	.12 / 13.5 / .226	.125 / 9.2 / .108	.100 / 9.2 / .087	.40 / 4.5 / .083	.30 / 4.5 / .062	.16 / 13.5 / .300	.12 / 13.5 / .226	.125 / 9.2 / .108	.100 / 9.2 / .087	.40 / 4.5 / .083	.30 / 4.5 / .062	
1	-	.98/1.00	.62/.64	.98/1.00	.68/.70	.96/.98	.62/.63	.98/1.00	.75	.96/1.00	.58/.62	.98/1.00	.66/.68	3/22/60, calibration adjustment, 20-minute warmup, fwd./aft, start 1:00 a.m., finish 4:00 p.m., turned set off.
2	2.26	.98/1.00+	.62/.64	.84/.88	.58/.62	.84/.86	.58/.59	.92/.93	.70/.72	.88/.94	.54/.56	.94/.96	.64/.66	3/23/60, 11:00 a.m., approximately 3-hour warmup, aft/fwd.
3	2.27	.98/1.00	.62/.64	.80/.82	.55/.57	.78/.80	.48/.50	.92/.94	.70/.72	.82/.84	.52/.53	.88/.90	.58/.60	3/23/60, 2:00 p.m., fwd./aft, turned out high and low alarm potentiometers if channel was checked. High/low alarms full-in, full-out; no difference was noted.
4	2.28	.98/1.00	.62/.64	.80/.84	.54/.57	.87/.90	.54/.56	.91/.92	.68/.70	.76/.78	.48/.58	.85/.87	.56/.58	3/23/60, ≈ 4:00 p.m., aft/fwd., turned set off.
5	1.98	.98/1.00	.60/.64	.82/.84	.58/.60	.88	.56/.58	.68/.70	.50	.58/.60	.38/.40	1.08 (Extrap.)	.80/.82	3/24/60, 9:15 a.m., 35-minute warmup, fwd./aft.
6	2.20	1.03 (Extrap.)	.62/.64	.88/.90	.60/.64	.80/.84	.52	.86/.88	.66	.82/.84	.52/.54	.98/1.00	.68/.70	3/24/60, 10:40 a.m., aft/fwd.
7	2.28	.98/1.00+	.60/.62	.88	.60/.62	.74/.76	.46/.48	.92/.94	.70/.72	.88/.90	.54/.58	.86/.90	.56/.58	3/24/60, 1:40 p.m., fwd./aft.
8	2.28	.96/.98	.60/.62	.76/.80	.52/.54	.72/.74	.44	.92	.70/.72	.82/.84	.52/.54	.94/.95	.54/.56	3/24/60, 4:20 p.m., aft/fwd.
9	2.17	.94/.98	.58/.60	.84/.88	.58/.60	.72/.74	.45/.46	.86/.88	.64/.65	.78/.79	.59/.60	.94/.96	.62/.66	3/25/60, start fwd. 9:30 a.m., start aft 10:25 a.m.
10	2.24	.96/.98	.61/.63	.80/.82	.54/.56	.74/.76	.46/.47	.91/.92	.70	.84/.86	.54/.56	.88/.92	.56/.60	3/25/60, 1:30 p.m., aft/fwd.
11	2.24	.98/1.00+	.66/.67	.78/.80	.54/.56	.83/.84	.51/.52	.91/.92	.68/.70	.76/.80	.48/.50	.78/.80	.51/.53	3/25/60, 4:00 p.m., fwd./aft.
12	2.22	.92/.98	.58/.61	.79/.86	.52/.62	.68/.70	.43/.44	.90/.92	.70/.71	.74/.78	.48/.50	.77/.79	.49/.51	3/26/60, 9:00 a.m., aft/fwd., turned set off.
13	1.95	.96/1.00	.62/.63	.90/.94	.65/.68	.82	.51	.86/.88	.66/.68	.70/.74	.45/.47	.96/.98	.66	3/28/60, 9:50 a.m., 15-minute warmup, fwd./aft, turned set off.
14	1.96	.96/.98	.60/.64	.88/1.00	.63/.69	.86/.88	.56/.58	.76/.78	.56/.58	.60/.62	.36/.38	1.09 (Extrap.)	.82/.84	3/28/60, 4:45 p.m., 15-minute warmup, aft/fwd., turned set off.
15	-	.96/1.00	.61/.63	.86/.92	.62/.66	.84	.53/.54	.84	.62/.64	.70/.76	.46/.49	.98/1.00	.68/.72	3/29/60, 1:35 p.m., 25-minute warmup, fwd./aft.
16	-	.96/1.00	.64/.66	.69/.73	.46/.52	.74/.75	.46	.88/.90	.68/.70	.76/.80	.48/.50	.92/.94	.62/.64	3/30/60, 2:20 p.m., fwd. and aft pickup cables interchanged, aft/fwd.
17	Check O.K.	.88/.90	.55/.58	.74/.78	.50/.52	.70/.72	.44/.46	.88/.90	.78	.68/.73	.43/.45	.86/.92	.58/.61	3/30/60, 4:45 p.m., fwd./aft.
18	-	.80/.86	.40/.42	.70/.74	.50/.66	.76/.78	.49/.50	.76/.78	.56/.58	.64/.68	.40	.98/1.00+	.70/.72	3/31/60, 8:55 a.m., aft/fwd.
19	-	.72/.74	.54/.56	.70/.74	.50/.52	.77/.80	.48	.70/.74	.53	.60/.62	.36/.40	1.00+	.70/.74	4/1/60, 9:00 a.m., fwd./aft.
20	-	.80/.82	.40/.42	.76/.78	.54/.58	.72/.74	.46/.48	.68/.70	.48/.50	.54/.60	.36/.38	.96/1.00	.70/.74	4/1/60, 4:43 p.m., aft/fwd., slide plate locked; cables returned to original pickups, set turned off.
21	-	.82/.86	.51/.54	.71/.78	.50/.55	.84/.86	.53/.54	.86/.87	.65/.66	.58/.60	.38/.40	.85/.91	.58/.60	4/4/60, 1:05 p.m., ≈ 4-hour warmup, fwd./aft.
22	-	.81/.84	.50/.52	.63/.73	.42/.50	.68/.72	.42/.44	.86/.88	.66/.68	.58/.70	.36/.42	.86/.91	.58/.60	4/4/60, 4:45 p.m., aft/fwd.
23	-	.76/.80	.47/.49	.67/.70	.46/.48	.72/.74	.44/.46	.75/.76	.56/.58	.56/.60	.36/.38	.96/.98	.66/.68	4/5/60, 9:17 a.m., aft/fwd.
24	-	.78/.82	.48/.50	.72/.76	.52/.54	.74/.76	.47	.80/.82	.60/.64	.60/.68	.40/.44	.90/.94	.60/.68	4/5/60, 2:20 p.m., aft/fwd.
25	-	.78/.80	.48/.50	.74/.76	.52/.54	.84/.86	.54/.56	.84/.85	.62/.65	.60/.62	.39/.41	.89/.91	.63/.65	4/5/60, 4:40 p.m., fwd./aft.
26	-	.70/.76	.48/.52	.66/.74	.46/.48	.76/.78	.46/.48	.86/.88	.65/.66	.58/.70	.36/.46	.82/.86	.54	4/6/60, 9:05 a.m., aft/fwd.
27	-	.70/.74	.44/.46	.60/.74	.42/.52	.79/.80	.49/.50	.85/.86	.63/.64	.62/.64	.40/.44	.82/.84	.54/.55	4/6/60, 4:45 p.m., fwd./aft.
28	-	.72/.76	.44/.48	.60/.70	.42/.48	.66/.68	.41/.43	.82	.62	.58/.66	.37/.44	.88/.94	.59/.63	4/7/60, 9:15 a.m., aft turned set off.
29	-	.46/.48	.29	.58/.62	.40/.45	.68/.70	.43/.44	-	-	-	-	-	-	4/13/60, 1:16 p.m., warmup.
30	-	.56/.58	.33/.34	.60/.64	.42/.44	-	-	-	-	-	-	-	-	4/13/60, 1:25 p.m., 20 warmup.
31	-	-	-	-	-	-	-	.58	.40/.42	.38	.23/.24	.98/1.00	.78/.80	4/13/60, 1:35 p.m., 30 warmup.
32	-	.70/.72	.42/.44	.60/.65	.40/.44	.74	.56/.58	.82/.84	.62/.63	.52/.62	.33/.37	.94/.96	.62/.66	4/13/60, 4:35 p.m., 4-hour warmup, aft/fwd.

16	-	.96/1.00	.64/.66	.69/.73	.46/.52	.74/.75	.46	.88/.90	.68/.70	.76/.80	.48/.50	.92/.94	.62/.64	3/30/60, 2:20 p.m., fwd. and aft pickup cables interchanged, aft/fwd.
17	Check O.K.	.88/.90	.55/.58	.74/.78	.50/.52	.70/.72	.44/.46	.88/.90	.78	.68/.73	.43/.45	.86/.92	.58/.61	3/30/60, 4:45 p.m., fwd./aft.
18	-	.80/.86	.40/.42	.70/.74	.50/.66	.76/.78	.49/.50	.76/.78	.56/.58	.64/.68	.40	.98/1.00+	.70/.72	3/31/60, 8:55 a.m., aft/fwd.
19	-	.72/.74	.54/.56	.70/.74	.50/.52	.77/.80	.48	.70/.74	.53	.60/.62	.36/.40	1.00+	.70/.74	4/1/60, 9:00 a.m., fwd./aft.
20	-	.80/.82	.40/.42	.76/.78	.54/.58	.72/.74	.46/.48	.68/.70	.48/.50	.54/.60	.36/.38	.96/1.00	.70/.74	4/1/60, 4:43 p.m., aft/fwd., slide plate locked; cables returned to original pickups, set turned off.
21	-	.82/.86	.51/.54	.71/.78	.50/.55	.84/.86	.53/.54	.86/.87	.65/.66	.58/.60	.38/.40	.85/.91	.58/.60	4/4/60, 1:05 p.m., ≈ 4-hour warmup, fwd./aft.
22	-	.81/.84	.50/.52	.63/.73	.42/.50	.68/.72	.42/.44	.86/.88	.66/.68	.58/.70	.36/.42	.86/.91	.58/.60	4/4/60, 4:45 p.m., aft/fwd.
23	-	.76/.80	.47/.49	67/.70	.46/.48	.72/.74	.44/.46	.75/.76	.56/.58	.56/.60	.36/.38	.96/.98	.66/.68	4/5/60, 9:17 a.m., aft/fwd.
24	-	.78/.82	.48/.50	.72/.76	.52/.54	.74/.76	.47	.80/.82	.60/.64	.60/.68	.40/.44	.90/.94	.60/.68	4/5/60, 2:20 p.m., aft/fwd.
25	-	.78/.80	.48/.50	.74/.76	.52/.54	.84/.86	.54/.56	.84/.85	.62/.65	.60/.62	.39/.41	.89/.91	.63/.65	4/5/60, 4:40 p.m., fwd./aft.
26	-	.70/.76	.48/.52	.66/.74	.46/.48	.76/.78	.46/.48	.86/.88	.65/.66	.58/.70	.36/.46	.82/.86	.54	4/6/60, 9:05 a.m., aft/fwd.
27	-	.70/.74	.44/.46	.60/.74	.42/.52	.79/.80	.49/.50	.85/.86	.63/.64	.62/.64	.40/.44	.82/.84	.54/.55	4/6/60, 4:45 p.m., fwd./aft.
28	-	.72/.76	.44/.48	.60/.70	.42/.48	.66/.68	.41/.43	.82	.62	.58/.66	.37/.44	.88/.94	.59/.63	4/7/60, 9:15 a.m.*, aft/fwd., turned set off.
29	-	.46/.48	.29	.58/.62	.40/.45	.68/.70	.43/.44	-	-	-	-	-	-	4/13/60, 1:16 p.m.,* 11-minute warmup.
30	-	.56/.58	.33/.34	.60/.64	.42/.44	-	-	-	-	-	-	-	-	4/13/60, 1:25 p.m., 20-minute warmup.
31	-	-	-	-	-	-	-	.58	.40/.42	.38	.23/.24	.98/1.00	.78/.80	4/13/60, 1:35 p.m., 30-minute warmup.
32	-	.70/.72	.42/.44	.60/.65	.40/.44	.74	.56/.58	.82/.84	.62/.63	.52/.62	.33/.37	.94/.96	.62/.66	4/13/60, 4:35 p.m., 4-hour+ warmup, aft/fwd.
33	-	.71/.73	.42/.44	.60/.64	.40/.44	.66	.40	.80/.82	.62/.64	.56/.60	.33/.38	.86/.88	.56/.58	4/14/60, 9:15 a.m., fwd./aft, turned set off.
34	-	-	-	-	-	-	-	.35	-	.28	-	.63/.66	-	4/15/60, 9:11 a.m., 11-minute warmup.
35	-	-	-	-	-	-	-	.40/.42	-	.28	-	.68	-	4/15/60, 9:16 a.m., 16-minute warmup.
36	-	-	-	-	-	-	-	.46/.48	-	.34/.40	-	.88/.92	-	4/15/60, 9:25 a.m., 25-minute warmup.
37	-	-	-	-	-	-	-	.52	-	.33/.40	-	.96/1.00	-	4/15/60, 9:31 a.m., 31-minute warmup.
38	-	.64/.66	.40/.42	.50/.58	.36/.40	.60/.62	.36	.62/.64	-	.62/.70	-	.90/.92	.78/.80	4/15/60, 2:53 p.m., aft/fwd., turned set off.
39	-	.33/.34	-	.44/.52	-	.56/.58	-	-	-	-	-	-	-	4/18/60, 9:24 a.m., 12-minute warmup.
40	-	.36/.40	-	.44/.52	-	.62/.64	-	-	-	-	-	-	-	4/18/60, 9:27 a.m., 15-minute warmup.
41	-	.48/.50	-	.52/.58	-	.70/.74	-	-	-	-	-	-	-	4/18/60, 9:42 a.m., 30-minute warmup.
42	-	.52/.54	-	.52/.61	-	.68	-	-	-	-	-	-	-	4/18/60, 9:53 a.m., 41-minute warmup.
43	-	.58/.60	-	.60/.70	-	.68/.70	-	-	-	-	-	-	-	4/18/60, 10:26 a.m., 1-hour-34-minute warmup.
44	-	.66/.70	-	.68/.70	-	.73/.75	-	-	-	-	-	-	-	4/18/60, 11:26 a.m., 2-hour-34 minute warmup.
45	-	.66/.68	-	.58/.68	-	.74/.76	-	-	-	-	-	-	-	4/18/60, 1:02 p.m., 4-hour warmup.
46	-	.73/.75	.44/.46	.54/.62	.36/.40	.64/.66	.38/.40	.82/.84	.62/.64	.54/.60	.31/.38	.68/.72	.44/.46	4/19/60, 4:22 p.m., 31-hour+ warmup, fwd./aft, turned set off.
47	2.27	.72/.76	.40/.42	.78/.80	.52/.56	.70/.72	.44/.46	.40/.42	.26	.42/.48	.28/.30	.78/.80	.56/.60	4/30/60, 10:21 a.m., 11-minute warmup, readjust Osc.1, was .84 v.r.m.s., adjust to 2.27 v.r.m.s., aft/fwd., turned set off.
48	2.70	.98/1.00+	.59/.62	.86/.96	.64/.72	.72/.74	.46/.48	.56/.58	.38/.40	.64/.70	.44/.50	1.06 (Extrap.)	.76/.78	4/30/60, 12:45 a.m., 11-minute warmup, increased Osc.1 to 2.70 v.r.m.s., noted period change, was 3.1982 M-S to 3.1992 M-S, fwd./aft, turned set off.
49	2.63	.94/.96	.57	.82/.86	.58/.62	.70/.72	.45/.46	.42	.27/.28	.42/.44	.28/.30	.78/.80	.55	5/2/60, 9:22 a.m., 12-minute warmup, no change in period, aft/fwd., turned set off.
50	2.70	1.18 (Extrap.)	.72/.74	.90/.98	.64/.70	.84/.88	.56/.60	.70/.72	.50/.52	.70/.72	.50/.52	1.32 (Extrap.)	.94 (Extrap.)	5/2/60, 2:05 p.m., 10-minute warmup, fwd./aft, no change in period.

* Total time equipment was off - 148 hours.
m - micrometer reading (inches)
f - frequency (cycles per second)
g - acceleration due to gravity
/ - indicates meter needle oscillation

2

Three tests were conducted on March 28 and 29 (test 13, 14, and 15), each with approximately a 20-minute warmup. The 2/rev. channels were both erratic and indicated a meter swing of one to one and one-half major divisions (1/10 full scale).

The unit was left "power on" from March 29 to April 7 (tests 15 through 28). On March 30 (test 17), the 3F channel, which had heretofore held a fairly steady reading, dropped one whole division. The 2/rev. channels continued to give erratic readings, and the average of all channels tended to be lower.

On April 1, a qualitative temperature test was conducted on the unit. This test was interjected between calibration tests 19 and 20. A heat lamp was placed approximately 3 to 5 inches from the top of the main chassis; the temperature in the vibration signal amplifier was recorded by thermometer. A record was kept of the calibrated output of the 1/rev. aft channel maintained at a constant .062g. Table 2 indicates the results of this test. Shortly after the heat lamp was turned off, a shop fan was turned on the open back face of the main chassis, and a forced ventilation was maintained for the balance of the test period. The calibration output reduced with an increase in temperature and returned to the original reading when the temperature was reduced. A lowering of temperature had the same effect.

TABLE 2
QUALITATIVE TEMPERATURE TEST, CHANNEL 1A

g	Time (min.)	Meter	Temp. (deg.)	Comments
.083	0	.98/1.00	91	Lamp Off
.062	0	.64/.68	91	"
"	6	.64/.68	92	Lamp On
"	10	.62/.68	94	"
"	18	.54/.58	96	"
"	24	.50/.52	97	Lamp Off
"	31	.52/.54	98	"
"	37	.56/.58	98	Fan On
"	43	.58/.60	94	"
"	47	.60/.66	92	"
"	49	.64/.68	90	"
"	49	.62/.64	90	Readjust Tach. Speed
"	52	.60/.63	89	"
"	55	.58/.61	88	"
"	60	.53/.57	86/87	"

The power was turned off on April 7, and the unit remained dormant until April 13, when it was observed that all channels were down considerably from the preceding readings (tests 29 to 33). Approximately 20 hours of warmup were required to bring the readings up to those recorded in test 28. The same problem was encountered on April 15 (tests 34 through 38) and again on April 18 and 19 (tests 39 to 46).

On March 26, a check had been run on the oscillators, and it was observed that oscillator number one voltage was down considerably from any previous readings. Oscillator number two was satisfactory and both frequencies were correct. The readings are recorded in Table 3.

TABLE 3
OSCILLATOR READINGS

Osc. No. 1 (Voltage - r. m. s.)	Warmup Time (min.)
1.26	1
1.36	7
1.45	15
1.58	30

As a result of this test, it was suspected that all tests subsequent to April 7 (tests 29 to 46) were conducted with a low output voltage from oscillator number one. This oscillator had indicated slow warmup characteristics in the past. Since the oscillator had indicated satisfactory operation at test 17 and since the power was maintained up to test 28, all tests up to this point are indicative of the operational characteristics of the unit after sufficient warm-up time.

Table 4 summarizes the results of calibration tests 2 through 28. The average of tests 2, 3, and 4 is taken as true calibration of the unit. The minimum and maximum readings recorded during this series of tests are noted, and the tests at which they were recorded are given in parentheses. An average slope for tests 13, 14, and 15 was computed, and together with the incremental change in meter readings, it was employed to calculate the error in percent of maximum g for each of the channels.

On April 30, the unit was turned on, and after 4 minutes of warmup the output of oscillator number one was .84 volts (r. m. s.) and the period was steady. The oscillator was adjusted to 2.27 volts (r. m. s.), and test number 47 was recorded. At the conclusion of this test, oscillator number one was readjusted to 2.80 volts (r. m. s.), and no change in the maximum reading for the 1F channel was observed. At 12.45 the set was turned on again, and after 2 minutes oscillator number one recorded 2.70 volts (r. m. s.). However,

TABLE 4
SUMMARY OF CALIBRATION TESTS 2 THROUGH 28

				Meter										
					Avg.									
					Tests	Tests			Increment			Percent Error		
Channel	m.	f.	g.	Min.	2 - 28	2 - 4	Max.	Slope	$-\Delta$	$+\Delta$	Total	(-)	(+)	Total
3F	.160	13.5	.300	(26 & 27) .70	.886	.99	1.03 (6)	4.8	.29	.04	.33	20.2	2.8	23.0
2F	.125	9.2	.108	(27 & 28) .60	.785	.83	1.00 (14)	12.5	.23	.17	.40	17.0	12.6	29.6
1F	.400	4.5	.083	(28) .66	.780	.841	.90 (3)	14.0	.181	.059	.24	15.6	5.1	20.7
3A	.160	13.5	.300	(20 & 5) .68	.880	.918	.94 (3)	2.8	.238	.022	.26	28.4	2.6	31.0
2A	.125	9.2	.108	(20) .54	.710	.85	.94 (2)	13.4	.310	.09	.40	21.4	6.2	27.6
1A	.400	4.5	.083	(12) .77	.969	.90	1.09 (14)	14.5	.130	.19	.33	10.8	15.8	26.6

m. - micrometer reading (inches)
f. - frequency (cycles per second)
g. - acceleration due to gravity

the period was observed to have changed from 3.1982 milliseconds to 3.1992 milliseconds. Contrary to expectations, all channels were up, but the 1F and 1A channels were off scale. Two additional tests were conducted on May 2 (tests 49 and 50). The oscillator number one voltage was steady, 2.63 to 2.80 volts (r.m.s.), and the period was unchanged at 3.1992 milliseconds.

On April 3, three oscillator tests were conducted. The results of these tests are summarized in Tables 5 through 7. In the first test the shake table and resolvers were dormant (i.e., zero frequency); the voltage output of oscillator number one was varied from 1.25 volts (r.m.s.) to 2.65 volts (r.m.s.), and the period was established. A variation of .0007 second over the range of voltages tested was noted. This is equivalent to approximately .05-cycle-per-second volt variation.

TABLE 5
OSCILLATOR TEST NO. 1, OSCILLATOR NO. 1

Period (msec.)	Voltage (r.m.s.)
3.1985	1.25
3.1986	1.50
3.1987	1.70
3.1988	2.00
3.1989	2.30
3.1992	2.65
3.1991	2.48
3.1990	2.38
3.1989	2.19
3.1987	1.77

The second and third oscillator tests were conducted with the shaker in operation at constant g shake. Test 2 was on the 1A channel with a .062g vibration (.03-inch single amplitude), and test 3 was on the 3F channel with a .226g vibration (.012-inch single amplitude).

TABLE 6
OSCILLATOR TEST NO. 2, OSCILLATOR NO. 1
(1A Channel, g = .062)

Period (msec.)	Voltage (r. m. s.)	Meter
3.1980/3.1989	1.55	.37/.38
3.1984/3.1991	1.86	.48/.50
3.1986/3.1993	2.25	.62/.64
3.1988/3.1996	2.48	.68/.70
3.1989/3.1997	2.75	.73/.75
3.1992/3.1200	3.00	.80/.82
3.1988/3.1994	2.45	.70/.72
3.1983/3.1992	1.90	.54/.56
3.1980/3.1989	1.53	.44/.46
3.1976/3.1988	.90	.16
3.1977/3.1988	1.14	.26/.28

TABLE 7
OSCILLATOR TEST NO. 3, OSCILLATOR NO. 1
(3F Channel, g = .226)

Period (msec.)	Voltage (r. m. s.)	Meter
3.1992/3.2000	3.09	.80/.82
3.1989/3.1997	2.81	.76/.79
3.1985/3.1994	2.50	.56/.58
3.1983/3.1993	2.26	.46/.48
3.1983/3.1991	1.97	.36/.37
3.1981/3.1989	1.50	.20/.21
3.1985/3.1991	2.13	.43
3.1985/3.1993	2.50	.58/.60

The oscillator output voltage was varied, and both the period and the meter output were recorded. The output frequency varied for a specified voltage by approximately ±.05 cycle per second, and the voltage, although specified as constant, was noticed to have a small change in amplitude (noticeable only on the scope when greatly magnified). The variation in metered output indicates approximately a 30-percent full-scale g/volt (r.m.s.) for the 1A channel and 20-percent full-scale g/volt (r.m.s.) for the 3F channel. To generalize, it would appear that a 2- to 3-percent error should be anticipated for each 100-millivolt change in oscillator voltage.

Observations

The forward channels appeared to be slightly more consistent than the aft channels during the initial tests (see tests 2 through 12). The second harmonic channels, 2F and 2A, gave occasional wide swings in meter readings. Most of the readings were within one small division (.02) on the meter, while the second harmonic channels averaged .04 or higher (see 2A, test 4; 2F, test 14; and 2F, test 27). The calibrated output of all channels tended to be reduced as the test was extended. Five of the six channels had given their highest reading by test 6. The remaining channel (2F) gave a high but erratic reading in test 14, and the highest steady reading was in test 6. The lowest readings recorded for the forward channels were recorded in tests 26 through 28. The aft readings were low in the mid-test region (tests 12 through 20). The warmup time appears satisfactory up to test 15. Tests 15 through 28 were under continuous power. The 3F channel indicated a pronounced and unexplainable break at test 17. Warmup time after test 28 was substantially increased (see tests 29, 34, and 39). The cause of this increase is believed to be the slow starting of oscillator number one. The tests conducted on the oscillator indicate a substantial dependence of the calibration on the output of the oscillator. Heretofore, the calibration had been considered to be essentially independent of the oscillator output. The variation indicated would explain in part the drift indicated in the several calibration tests.

The following observations can be made from the results obtained from the series of tests by referring now to the list of potential sources of calibration drift:

1. Band-Pass Filter and Oscillator Controls - Variation in the basic characteristics (frequency and amplitude) of these two components of the circuit would result in a multifold and complex problem for analysis. The low-frequency oscillator (number one) demonstrates both a most pronounced change in amplitude and to a lesser degree a change in frequency. The change in oscillator output demonstrated a change in meter reading of the order of 20 to 30 percent of maximum g per volt change in oscillator amplitude. This could be the explanation for the variation noticed in the calibration tests. However, an explanation of the calibration tests indicates that the calibration drift observed is not a simple relationship with the oscillator amplitude. Frequency also varies with the amplitude of the oscillator

(± .05 cycle per second). Since the calibration output depends on the frequency match of the oscillators and controls and on the pass-band characteristics, even a small change in the frequencies of either would result in a calibration change, and, depending on the initial match of the controls and band pass, it could increase or decrease the calibration output. The tendency would be for the calibration output to go down with any change in frequency or pass characteristics if the initial match of the components is assumed to be precise.

2. Resolvers - Two adverse characteristics were observed in the resolver operation. The 2/rev. channels indicate occasional surges in the calibrated output from one to two major divisions on the meter. This characteristic has been observed in the past and is correctable by replacement of the resolver. This is due to a binding or locking of the resolver shaft because of a bearing failure in the resolver. The second characteristic observed was related to oscillator number one. The oscillator frequency and amplitude characteristics change slightly when the resolvers are rotated. This could be caused by either a mismatch in impedance or a loading effect.

3. Vibration Pickup - No direct observations of the vibration-pickup characteristics were made during this series of tests. The unit employed was a Shaevitz VG-10 accelerometer with a natural frequency of 65 cycles per second. A recent publication of Shaevitz indicates a product improvement of this line, making it possible to use a VG-5 unit. This would very nearly double the output signal level of the unit and reduce the requirements for the amplification stages. This component change should be incorporated on any additional units constructed.

4. Transistors - No transistor failures were observed throughout this series of tests. It would appear that all transistors are operating within specifications; therefore, the drift in calibration observed in this series of tests could not be directly attributed to faulty transistor operation.

5. Alarm Relays - The alarm relay circuits were turned out prior to calibration test 3. The observed effects could not be attributed to relay operation.

6. Shake Table - The shake table has accumulated several hundred hours of operating time with accumulated wear on the working parts. Considerable backlash, undoubtedly contributing to harmonic distortion of the vibration, is observable in the gear train. It is believed that the absolute value of the displacement has shifted since the table was originally put into operation. However, the change in amplitude would not account for the observed calibration drift.

Conclusions

The tests conducted indicate the practicality of utilizing equipment of this type as a means of effectively sensing, analyzing, and indicating to the pilot the vibration characteristics that exist in the helicopter, thus alerting him to an adverse vibration condition. However, in its present stage of development, the system requires frequent calibration checks because of its inherent tendency to drift.

In the particular unit tested, an output change in oscillator number one appears to be the principal (although not the only) cause of calibration drift. In operational use it would be relatively simple to check this element of the system daily or at preflight, and to adjust the output in the event that it was outside of tolerance. Because of the installation time required, it would not be practical, however, to perform a complete calibration check for the entire system. It is not possible at this time to establish a definitive period between calibrations. It is recommended that the units be installed and tested in helicopters and that an initial period of 10 hours of flight time between calibration checks be established. This time should be lengthened as knowledge of the operational characteristics becomes more extensive.

Serious consideration should be given to a modification or redesign of the oscillator circuit. The present circuit appears to be satisfactory for the immediate purpose; however, maintenance time and utility of the system could be improved.

The qualitative temperature tests conducted indicate a limited range to maintain calibration. It is recommended that a more detailed and comprehensive temperature-test program be undertaken to establish temperature compensation for the unit.

/s/ Hugh L. Donnelly
/t/ HUGH L. DONNELLY
Project Engineer

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